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Volume 52 Number 5 September/October 2018

State of Technology Report 2018

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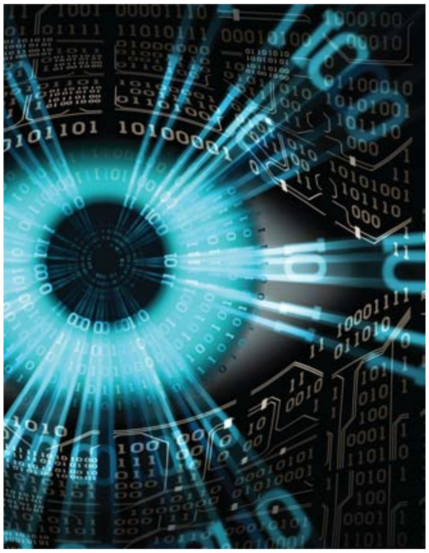

Cover images: Today's marine technology is riding a wave of innovation. Artificial Intelligence is expected to have the most impact over the next decade, especially as third wave contextual adaptation evolves.

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State of Technology Report 2018

Guest Editor: Donna M. Kocak

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FOREWORD

State of Technology Report: Maritime Technology in 2018

Donna M. Kocak
President, Marine Technology Society

Harris Corporation

Today's marine technology is riding a wave of innovation spurred by advances in consumer technologies, competition in military and defense, efficiencies to improve profit margins, and other emerging developments. This is truly an exciting time to be a part of the ocean community.

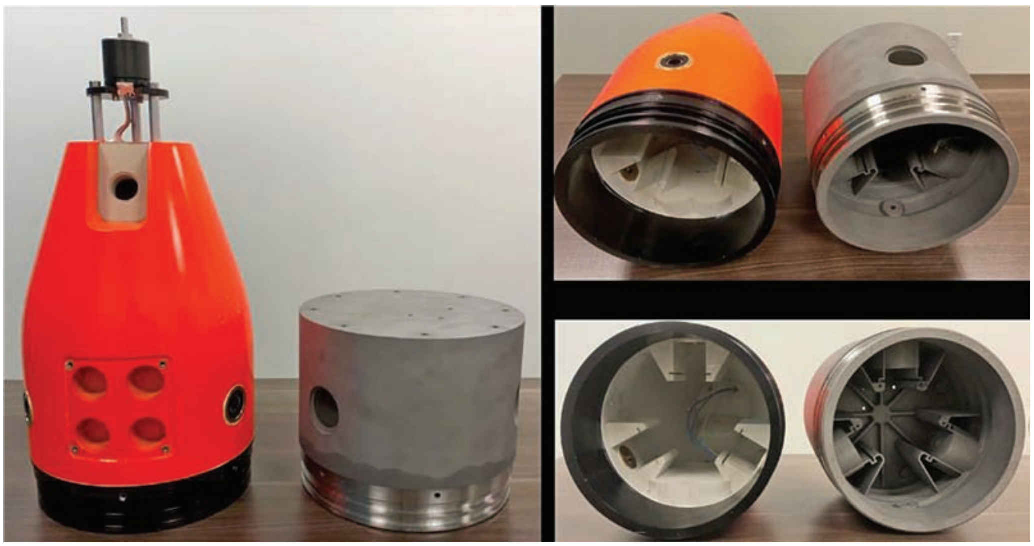
Advances in Consumer Technologies

Since the last State of Technology Report in 2013 (Kocak, 2013), many advances in consumer technologies have been adopted by the marine sector. 3D printing is a good example. Patented in the mid-1980s, 3D printing became widely available in 2011 (Flynt, 2017). Some 3D printed maritime applications include ship rudders, a submarine prototype for the U.S. Navy, spare parts for the America's Cup 2017 boat race, turbines for renewable tidal current energy, and micro-unmanned untethered vehicles (UUVs; Hedstrom, 2015; 3Dnatives, 2017; Manley & Smith, 2018). Figure 1 illustrates two Riptide micro-UUV modular sections printed in nylon and titanium for shallow (300 m) and deeper (1,500 m) depth operations, respectively. The ability to print 3D prototypes prior to finalizing designs offers an efficient means to visualize, evaluate, and rapidly adjust configurations. The U.S. Navy and Marine Corps have integrated 3D printing into their ship maintenance and logistic supply chain. The main advantage, especially at sea, is the ability to print spare parts and tools on demand—when and where they are needed. A disadvantage is lack of economies of scale. In the future, we may see realistic 3D "bio" printing of shark skin or fish fins for bio-inspired vehicles (perhaps contributed by members of our new MTS Bio-Inspired Marine Systems Committee), inspired by advances in the medical field where organs and custom facial implants have been 3D printed. We may also see 3D printing of electronic circuits and RF systems such as waveguides, lenses, and antennae that consist of complex shapes and conformal systems that are difficult to achieve in traditional manufacturing. Worldwide, 3D printing services and products are reported to be worth over $7 billion (McCue, 2018), and this trend is expected to continue to increase well into the 2020s.

The Internet of Things (IoT) represents another example of a consumer technology finding its way into the marine sector. One envisioned venture is an offshore aquaculture facility that connects sensor arrays measuring phytoplankton biomass and real-time depth, temperature, conductivity, and dissolved oxygen to the Internet ("An Ocean Internet of

FIGURE 1

3D printed nylon (orange) and titanium micro-UUV modular sections (photo courtesy of Riptide).



Things"; Walsh, 2015). IoT platforms aggregate large data sets and statistically processed data using predictive analytics. From this, data-driven decisions can be made to improve commercial productivity and potentially lead to ways of gaining a competitive edge. In coastal regions confronted with water shortages, as in California, offshore aquaculture can substitute for agriculture. Having the ability to grow U.S. seafood supplies, independent of global geopolitical tensions, may one day be essential to prevent food shortages and risks to food safety. It is estimated that the number of IoT-connected devices may reach 38.5 billion in 2020, up from 13.4 billion in 2015 (Walsh, 2015).

The first two commentaries in this special issue, by Spinrad and Atmanand et al., further emphasize the importance of growing and maintaining a sustainable ocean economy. Machine learning and data analytics are central to processing large amounts of data and thus will be integral to the "New Blue Economy."

Competition in Military and Defense

The military has an immediate need to maintain technical superiority and better protect its warfighters. Technology advances are necessary, but still not sufficient, to defend against ever-changing weapons, biothreats, cyber, and other attacks. Speed of development is essential for turning technology advances into capability. One important area of investment is in artificial intelligence (AI) (DoD, 2018). Teaching machines to think like humans has been a long sought-after capability dating back to the 1950s (Anyoha, 2017). The current state of technology applies logical rules and/or neural networks designed from statistical models and trained on massive data sets to solve specific problem domains. A recent exception where a large data set is not required to train the neural network is the AlphaGo Zero program that learns "from scratch" through self-play reinforcement (Silver et al., 2017). AI methods are being used in many maritime applications. One recent example is the Defense Advanced Research Projects Agency (DARPA) Anti-Submarine Warfare Continuous Trail Unmanned Vessel that was recently transitioned to the Office of Naval Research, shown in Figure 2. Referred to as *Sea Hunter*, this unmanned surface vehicle is fully autonomous and can operate for months at a time, in accordance with maritime laws and practices for safe navigation. AI algorithms direct *Sea Hunter* on its primary mission, which is to navigate in search of mines and submarines (McCaney, 2018). Although the Navy continues to test and explore the vehicle's capability and new man-machine collaborative missions, a second vessel is being built. This will expand missions to include collaborative tandem operations between the two unmanned vessels, in addition to other missions involving manned and other UUV assets (including air drones) (Trevithick, 2018). Collaborative unmanned missions, as well as unmanned battles such as the first reported air drone to shoot down another air drone (Mizokami, 2018), are likely to be the future in warfighting.

Rolls-Royce is developing an autonomous naval vessel with a range of 3,500 nautical miles, capable of 100-day-long missions (Ghaswalla, 2017). The vessel is intended to perform a range of roles including patrol and surveillance, mine detection, and coastline watch. It will detect and track surface objects through Rolls-Royce's Intelligent Awareness System, which uses Google's Cloud Machine Learning Engine for training. Rolls-Royce is using this same technology to develop commercial autonomous shipping vessels (Kingsland, 2018). An integral function in autonomous commercial ships is the ability to automatically detect and communicate with other ships using speech recognition (Morely, 2017).

The next article in this issue, authored by Rinnan, discusses new enablers for autonomy in dynamic positioning (DP) systems. DP is an important feature for both manned and unmanned vessels. The MTS Dynamic Positioning Committee contributes significantly to this field by publishing Technical and Operational Guidance Notes, which have been advocated by the U.S. Coast Guard (MTS DP Committee, 2018).

Another crucial area for defense is cybersecurity and infrastructure (DoD, 2018). MTS has also recently established the MTS Cybersecurity and Infrastructure Committee to provide a forum for this industry sector currently facing a global challenge. Recent government funding has been invested on blockchain technology, originally adopted by the banking industry, to track information integrity (Richmond, 2017). Blockchain essentially tracks each time a system or piece of data is viewed or modified and records the user's ID and the date and time of the occurrence. A similar program at DARPA is SafeDocs, where the

FIGURE 2

DARPA's ACTUV *Sea Hunter* prototype (DARPA, 2018c; photo courtesy of DARPA).

goal is to have the software recognize and reject malicious electronic data without human intervention (DARPA, 2018b).

The next two articles in this special issue, by Koola and McGillivary (both members of the new MTS Cybersecurity and Infrastructure Committee), address the importance of cybersecurity in the maritime domain not only from a technology perspective but also through policy. Another excellent reference on cybersecurity in maritime is Hiller (2017).

Efficiencies to Improve Profit Margins

Industry always strives for greater efficiencies and cost savings to maximize revenue, and to do so often relies on emerging technologies, tools, and processes. Commercial shipping and offshore energy are two maritime examples where small savings in processes can realize substantial gains. In commercial shipping, for example, predictive analytics can be used to analyze real-time satellite Automatic Identification System information, meteorological and environmental data, and ship response models to find more efficient ship routes that may result in substantial fuel savings (Kocak & Browning, 2015; StormGeo, 2018). Similar AI methods can be used to find more efficient routing of cargo for shippers, freight forwarders, and carriers. When the number of ships and cargo containers are considered, as well as the various cost influences (oil prices, weather, fuel consumption rates, etc.), any optimization in travel time, cost, and resources needed to move the cargo may save tens of thousands of dollars a day per ship (Ijaz, 2018).

Because of the cyclic nature of the oil and gas industry, maintaining efficient operations across upstream and downstream activities are key to survival. One area where AI has recently been used to optimize performance is in well production. In the production business, it is estimated that 80% of potential increases in an oil field come from roughly 20% of the wells. ConocoPhillips sets out to identify which wells were in the 20% group. By using data previously collected from the wells, they were able to apply predictive analytics to determine where best to implement workflow optimizations. Production increased 30% where these optimizations were made. Over 3 years, using an assumed net price of $40 per barrel, this improvement would yield an additional $1 billion in revenue (Ward, 2016).

The next article in this issue, by Hartog et al., reviews the state of the art in distributed optical fiber sensing; a method that is commonly used to monitor and collect data in downhole wells. The authors also discuss several other uses such as sensing geohazards, chemicals, infrastructure integrity, and intruders (geofencing). Next, Davis et al. survey deep-ocean borehole observatories for long-term monitoring of hydrologic, geodetic, and seismic events. Sensors used in both articles provide large, real-time data sets that support the use of predictive analytics and machine learning.

Other Emerging Developments

There are some other developments in their initial stages that have the potential to become disruptive. Just as smartphones have changed our everyday lives, more incrementally than disruptively, some of the technologies discussed above may evolve into true disruptors. A recent ranking of the 30 emerging technologies that are expected to have the most impact over the next decade (2018–2028), based on Wikibrand's Digital Periscope study (Digital Transformation, 2018), is shown in Figure 3. The study took into consideration (1) current and projected size in terms of direct and indirect revenue, (2) future segment growth rate and scale of adoption, (3) claimed perception of impact on the future (from survey responses), (4) current "chatter value and buzz" via Google and social media, and (5) "knock-offs" and interactions with other technologies and industries. Whether or not you agree with this list and rankings, it offers a snapshot of emerging technologies that may bring new benefits to the maritime domain. A few of these technologies are discussed in more detail below as they relate to recent advances and the remaining articles in this issue.

AI is the highest ranked technology, expected to have the most impact over the next decade. Up until now, we have discussed AI in terms of its current state. Today's AI, however, is not yet able to *think and understand contextual information* like humans and therefore is

FIGURE 3

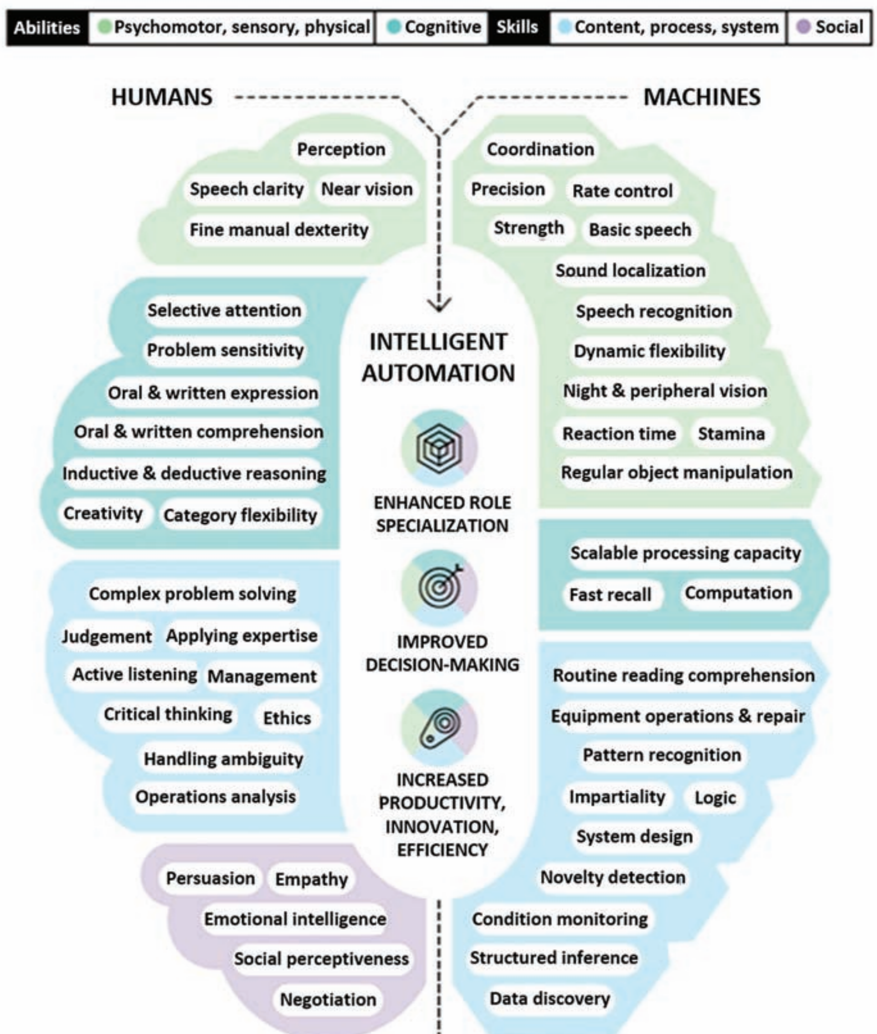
The 30 technologies of the next decade (Digital Transformation, 2018).

unable to *learn and adapt to changing situations*. When an AI algorithm is given unexpected or purposely misleading data, the results can be erroneous. This limits the autonomous capability of today's robots. At D60, DARPA announced a new $2 billion campaign to explore ways of achieving the next level of AI, referred to as the "third wave" (Heckman, 2018; DARPA, 2018a). Figure 4 compares the cognitive abilities and skills of a human to those of a machine—that is, what we are currently able to teach machines using "first wave" (rules-based) and "second wave" (statistical neural networks) AI techniques. Perhaps in some future State of Technology Report we will be able to describe how the third wave of AI research has increased the cognitive and social skills of a computer.

Advanced materials are playing an increasingly important role in the maritime domain. New antifouling microparticle nanocoatings can minimize biofouling and its associated drag and turbulence (Tripathi, 2016), nanoparticles and glass microspheres can control the density of a microcable (Abouraddy et al., 2018), and energized carbon nanotubes can provide noise-canceling of incoming sonar pings (Analysis, 2011), to name just a few. Contributions in this issue by Kery and Cole and Peters discuss the use of new

FIGURE 4

Comparing human-machine "intelligence" (Abbatiello et al., 2017).[1]



[1]Sources: Deloitte LLP, *Talent for Survival: Essential skills for humans working in the machine age*, 2016; Deloitte LLP, *From brawn to brains: The impact of technology on jobs in the UK*, 2015; Jim Guszcza, Harvey Lewis, and Peter Evans-Greenwood, *Cognitive collaboration: Why humans and computers think better together*, Deloitte University Press, January 23, 2017; Carl Benedikt Frey and Michael A. Osborne, *The Future of Employment: How Susceptible Are Jobs to Computerisation*?, University of Oxford, September 17, 2013; O*NET, U.S. Department of Labor.

materials in mooring and buoy systems. MTS has an active Buoy Technology Committee, led by Cole, that holds biannual workshops to share the state of the art in this important field.

Another early development, featuring both advanced materials and energy technology, employs carbon nanotubes spun into yarns less than a millimeter thick to generate power from constant motion (Revell, 2017). Currently, the yarns have been used to generate enough power to run a light-emitting diode (LED). In the future, researchers envision using a different configuration of these yarns in the place of batteries to power small buoy sensors from wave motion. In this issue, Copping et al. discuss marine renewable energy markets for many maritime applications. Vishwanath et al. discuss lead acid battery technology compared to other battery types and analyze battery performance under pressure.

Mobile/social Internet and live video streaming has, for many years now, been very effectively adopted in and successfully exploited by our maritime community. Dr. Robert Ballard's Nautilus Expeditions have been providing live video streaming to an Internet portal during their ocean exploration expeditions (Nautilus Live, 2018). The public, students, educators, and scientists watch and participate in live shore-based interactions. This opens the opportunity for anyone to explore the seafloor and make new discoveries alongside the scientists at sea. The final two pieces in this issue, a commentary by Cook and article by Kohnen, discuss ways technology—whether it is through the Internet or visibly diving to the depths—is helping us learn more about our oceans. Both also illuminate key tenets of MTS: to promote and improve marine technology-related educational programs and to meet, share discoveries and developments, and hold peer discussions with professionals and practitioners in the ocean community such as at the annual meeting held by the MTS Manned Underwater Vehicle Committee (chaired by Kohnen).

In conclusion, there have simply been too many technological advances, both implemented and emerging, to address them all in one Special Issue of the *Marine Technology Society Journal*. This is a very encouraging problem to have. As a result, we will be publishing Volume 2 of The State of Technology Report in 2019. Among the topics we hope to highlight will be biological concepts including persistent subsea monitoring and applications of DNA (deoxyribonucleic acid), fifth-generation wireless (5G) in the maritime realm, quantum control of molecules, small satellite constellations for enhanced maritime domain awareness, and more. As always, we invite and encourage our readers to become our contributors and are hopeful that some of you will contact us to offer your discoveries and developments in the form of a manuscript for this next issue.

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COMMENTARY

Ocean Economic Potential

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The economic potential from the world oceans is huge, immediately attainable, and—most importantly—sustainable. Historically, the value propositions aligned with marine technology have been associated with extraction economies, such as minerals or fisheries. A lot of effort is now being put into the latter to ensure that it can be sustained in a meaningful manner for decades to come, and although those components of the blue economy deserve continued critical technological investment, we have an exciting opportunity before us: an opportunity many are calling the "New Blue Economy."

What is this new economic potential? In short, it is a knowledge economy based on the exploitation of data and information; new knowledge allows us to make predictions and projections about marine environments and processes, all of which can be monetized into important, marketable products and services. The New Blue Economy will become an emerging developer of new requirements for marine technology. Consider the following examples of how our new capabilities for accurate and reliable ocean observing will serve emerging markets. One can easily imagine commercial enterprises providing the following specific products and services:

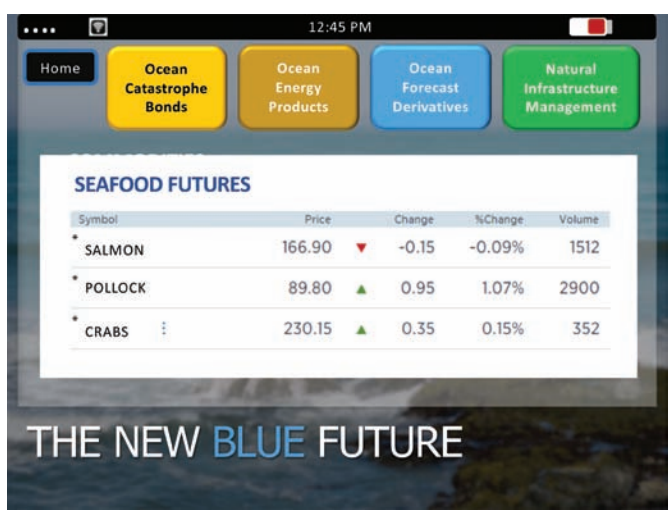
- Emergency response: Geographically specific baseline environmental characterization of local flora and fauna to provide accurate assessments of natural hazard damages after man-made site damage
- Infrastructure design: Detailed estimates of localized sea level rise predictions to support long-term (decadal) planning for port design and coastal community development
- Optimized commercial shipping: Tailored forecasts of currents, hydrography, and bathymetric changes to optimize load-out of commercial shipping vessels
- Public health: Community-specific and species-specific predictions of harmful algal blooms, with 3- to 7-day lead times.

These data-based products and services can support improved performance in an extraordinarily diverse cross-section of business sectors, from commercial shipping to public health and to land-use planning. In many regards, this vision is not dissimilar to what was projected (and subsequently realized) for what is now the commercial weather services industry (an industry of approximately $10B annual revenues and roughly 10,000 jobs). I would argue the diversity and breadth of applicability of the New Blue Economy will eclipse the applicability of the commercial weather sector by roughly an order of magnitude (Figure 1).

In this context, we must continue to consider the ever-expanding breadth and diversity of potential commercial applications for marine technology. Advances in marine technology have historically depended as much on the "pull" from applications as the "push" from scientific developments. For example, the needs of various industries (notably oil and gas) have encouraged aggressive development of

FIGURE 1

By 2030, it will be common to use next-generation search engines to search the physical world and make investments based on forecast products.



both remotely operated and autonomous underwater vehicles. And, even absent specific operational requirements over the last several years, the scientific community discovered a broad array of new sensing technologies and methodologies (e.g., doped fiber optics and *in situ* genetic analytical techniques), which soon found applications in a broad array of marine industries. This legacy of balancing innovation and mission relevance—a paradigm central to the mission of the Marine Technology Society—has positioned our community to move into a new and exciting domain of technological development. The current explosion of scientific discoveries and emergent applications, pushing and pulling, respectively, new marine technologies, makes the immediate future a particularly dynamic period in our community's history. Examples of technological development, including biomimetics, exascale computing, and miniaturization, are immediately relevant. The potential of the Internet of Things[1] also holds great promise for the New Blue Economy, as does the power of high-performance computing…what can IBM's Watson do for our ocean economy? Challenges for this activity will include how we choose to engage with seemingly unrelated technical communities and how those technologies are adapted to meet marine needs.

In summary, we are on the edge of an exciting development on ocean economic potential. The traditional economic sectors associated with marine technology are soon to be expanded by our new-found expertise in measuring, monitoring, and observing the marine environment, with incumbent accuracy and dependability. All of which will make the New Blue Economy a reality very soon.

[1]The Internet of Things, a phrase first coined by a British visionary named Kevin Ashton in 1999, has many definitions, but a simple one, derived from Techopedia (www.techopedia.com) states that "The internet of things (IoT) is a computing concept that describes the idea of everyday physical objects being connected to the internet and being able to identify themselves to other devices."

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COMMENTARY

Blue Economy of India and Technology Initiatives II

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ABSTRACT

With land-based resources depleting fast, sustained harvesting of ocean resources with an appropriate trade-off between economic growth, social needs, and the health of the ocean environment is essential. India, with an over 7600-km-long coastline, an exclusive economic zone of 2.3 million km^2, and seeking extension for additional 560 km, has initiated blue economic policies for leveraging the growth of the national economy. The first part of the paper presented in the OCEANS '18 conference in Kobe discussed the technology initiatives to harness the vast living and nonliving blue economic resources in India, including deep-ocean minerals, hydrocarbons, renewable energy, ocean desalination, and bioprospecting. This paper describes the activities carried out related to the activities undertaken by the National Institute of Ocean Technology (NIOT) in the areas of coastal protection, cyclone and tsunami early warning systems, coral habitat observations, sustainable fishing, and numerical studies carried out to understand the influence of natural gas leaks on deep-ocean ecology.

Keywords: coastal protection, early warning, coral, fishing, natural gas leaks

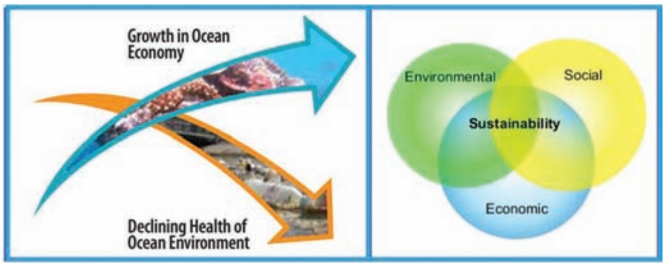
Introduction

Oceans, with an estimated asset value of US$24 trillion and an annual value of goods and services of US$2.5 trillion covering fisheries, transport, tourism, hydrocarbons, minerals, renewable energy, and bioresources are a promising strategic frontier for water security, food security, and economic growth. Subsequent to the foundations of the 2012 Rio+20 United Nations conference on sustainable development and the Goal 14 of the Global Sustainable Development 2030 announced in 2015 toward the sustainable development of ocean resources, the Indian Ocean Rim Association (IORA) blue economy dialogue was held in Goa during August of 2015. The Goa declaration stressed the need to identify the thrust areas of the blue economy, which are to be placed on the national strategic focus. The Indian Government's apex think tank, National Institution of Transforming India, has started discussions to formulate policies and strategies toward an integrated approach (United Nations General Assembly, 2017; Life Below Water: Why It Matters, 2016). The aim is to leverage India's blue economic potential to be on par with other major nations including the United States, China, and the European Union, whose blue economies are estimated to be about US$1.5 trillion, US$1 trillion, and US$0.5 trillion, respectively (FICCI Task Force, 2017). The pillars essential for transforming the traditional "Ocean and Marine Economy" to a "Blue" or "Sustainable" economy requires appropriate governance in sustained utilization of the ocean, coastal and marine economies, vision, technology, management, monitoring, and time-bound regulatory reforms. Hence, the fast emerging blue economy paradigm of India, which includes fishing aquaculture, ocean renewable energy, tourism, ocean commerce, and deep-ocean mineral and hydrocarbon exploitation, requires proper estimation of the size of the opportunity, nature of risks involved, identification of sustainable ocean asset investment, investment framework, and scaling up the capital investments of the blue industries. India, with its geostrategic status as a maritime nation with a long coast line, is a key member in the IORA intergovernmental organization, comprising 21 member states and nine dialogue nations aimed at strengthening regional cooperation and sustainable development within the Indian Ocean region. Discussions have been initiated with the IORA states including Mauritius, Seychelles, Bangladesh, Thailand, and South Africa, which have already enacted blue economy policies (IORA, 2015).

With blue economic activities including extraction of nonliving resources, harvest of living resources,

FIGURE 1

Concept of the sustainable blue economy (Life Below Water: Why It Matters, 2016; FICCI Task Force, 2017).



ocean commerce, and tourism in the uptrend, these economic activities should be in balance with the long-term capacity of ocean ecosystems to remain resilient and healthy (Figure 1). Hence, marine ecosystem management with appropriate technologies are essential for monitoring ocean health, likely natural hazards to the coastline, and threats to sensitive marine ecological systems such as beaches, fish stocks, coral reefs, and mangrove forests, which are recognized as natural capital assets.

Ocean State Monitoring

Because of the unique geography, more than 95% of major global tropical cyclones (TC)-based disasters have taken place in South Asia, with the frequency of intense cyclones on the uptrend, due to climate change (South Asian Disaster Knowledge Network, 2009; Unnikrishnan et al., 2011). The Indian maritime zone, which is dominated by a range of economic activities, has been perennially plundered by the fury of TC. Moreover, the tsunamigenic zones in the Andaman-Sumatra trench (Bay of Bengal) and the Makran coast (Arabian Sea) pose an ever-present tsunami threat to the long coastline. The Indian Ocean observational network established by the Ministry of Earth Sciences under the Indian Ocean Observation System is configured for real-time and delayed-mode coastal and offshore observations, facilitating data assimilation and real-time validation of the operational nowcast/forecast of the ocean variables in and around the Indian Seas. The network comprises offshore and coastal-located moored surface buoys, acoustic Doppler current profile moorings, deep-ocean wave buoys, coastal wave rider buoys, equatorial current meter moorings, and tsunami buoys for deep-sea water-level measurements. Also part of the network are Argo profiling floats, drifters, gliders, ship-borne observations such as expendable bathythermographs, expendable conductivity/temperature/depth profiling system, automatic weather stations, wave measurements from ships, conductivity-temperature-depth data, land-based high-frequency radars, and coastal tide gauges. In addition, the network includes the National Institute of Ocean Technology (NIOT)-operated Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction mooring network and the Ocean Moored Buoy Network for Northern Indian Ocean buoys networks (Ravichandran, 2015). To date, the moored data buoys are deployed in more than 650 locations (Figure 2) ranging from coastal waters to the deep ocean, spanning between 63°E to 93°E and 6°N to 20°N for collecting meteorological, water surface, and subsurface parameters, as well as tsunami water level data. The collected data are transmitted to the NIOT Mission Control Center located at NIOT in

FIGURE 2

Moored surface buoys deployed in Indian waters (Venkatesan et al., 2013).

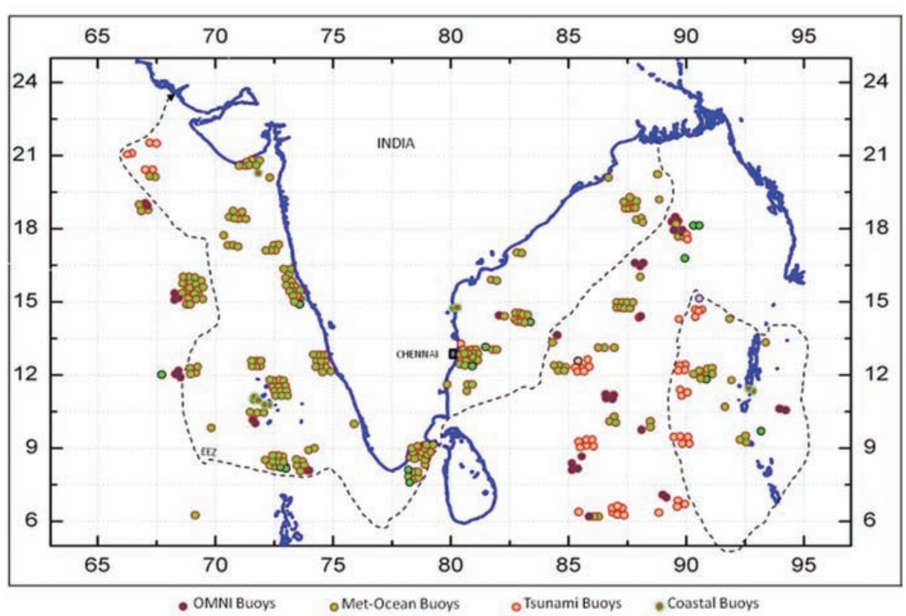


FIGURE 3

Strategic placement of the tsunami buoys.

Chennai and to the Indian Tsunami Early Warning Center (ITEWC) at the Indian National Centre for Ocean Information Services (INCOIS), Hyderabad (Venkatesan et al., 2013).

The tsunami buoys are moored at strategic locations close to the Andaman-Sumatra subduction fault in the Bay of Bengal and Makran fault in the Arabian Sea (Figure 3). During a tsunami event, the sea level data inputs from tsunami buoys serve as critical input to the ITEWC prerun scenario database, which computes the tsunami travel times and wave run-up wave heights, which are essential for the timely generation and dissemination of tsunami advisories. The ITEWC has been serving as the primary source of tsunami advisory for India and as a tsunami service provider for the entire Indian Ocean region (Srinivasa Kumar et al., 2016).

During the past two decades, the Indian moored buoy networks, which were matured to Safety Integrity Level 4 of on-demand safety reliability with appropriate healthiness monitoring interval, have detected more than 41 cyclones and 11 water-level change events associated with tsunami waves (Figure 4) (Venkatesan & Vedachalam, 2018). The data acquired during various events served as important inputs to various agencies, including the Indian Meteorological Department, and the scientific observations were used for understanding Indian Ocean dynamics for improved modeling of the evolution of seasonal monsoons and cyclones. The supercomputer Pratyush established at the Indian Institute of Tropical Meteorology in Pune and the National Center for Medium Range Weather Forecasting in Noida augments India's capability to improve weather and climate forecasting services (Venkatesan, 2017).

Shore Line Protection

Healthy coastal ecosystems providing protection from natural hazards, coastal erosion, and rising sea levels in low-lying and exposed delta regions are essential for interruption-free blue economic activities. Coastal erosion due to cyclone events and anthropogenic activities degrades the coastal infrastructure and livelihoods, thus affecting prime coastal land and tourism. Coastline-specific solutions based on the sedimentation process and littoral drift are undertaken in various Indian ports by NIOT for effective erosion control. In Kadalur-Periyakuppam village near Chennai, submerged shore parallel offshore dikes of 200-m lengths made of geosynthetic material filled with fine sand are being installed over 1.2 km in order to protect the beach from severe erosion, which affected the shoreline during the recent TC (Figure 5) (Kiran et al., 2015). The Indian

FIGURE 4

Water-level change during the 2015 tsunami event.

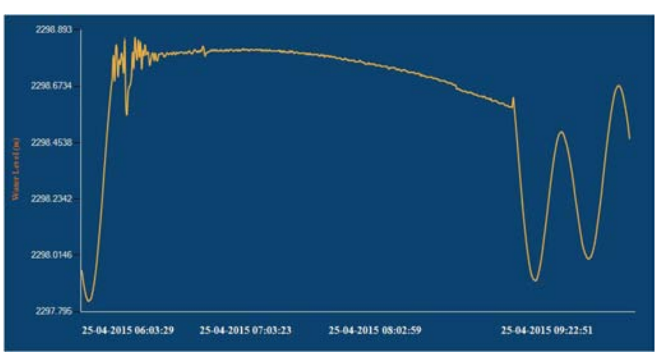


FIGURE 5

Dike laying off Kadalur Periyakuppam.

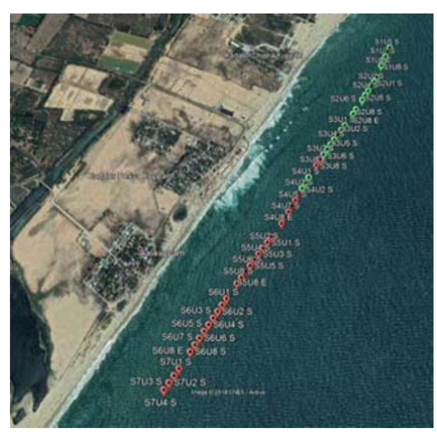
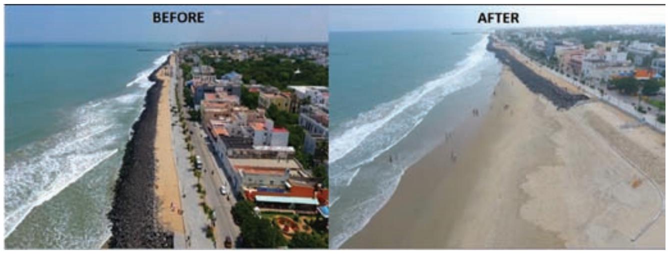


FIGURE 6

Beach formation near New Pier.



shorelines that are sensitive to erosion are being monitored with measures initiated in coordination with the respective local state administration.

The coastline of historical Puducherry (formally Pondicherry) on the east coast of India suffered severe coastal erosion due to natural causes and reorientation of the coast as a result of port breakwaters. Various mitigation measures including the construction of sea walls and groynes were not effective, and they resulted in erosion shifting farther north. In order to identify a long-term solution, a pilot beach nourishment project supported by numerical studies was executed based on long-term shoreline changes using satellite data and measurements taken during various seasons. The efforts resulted in the formation of a wide beach near New Pier (Figure 6).

Based on these encouraging pilot nourishment results, restoration of the lost beach all along Puducherry City is being undertaken with a proposed hybrid solution (Figure 7) involving beach nourishment with 0.45 million m^3 of sand and two reefs. The solution, in addition to beach restoration, will help increase the life of the nourished beach and minimize the effect of erosion on the northern side. The construction of the northern reef is in progress (Figure 8), and the construction of the southern reef is planned in the next phase (Prasad, 2017).

FIGURE 7

Proposed hybrid solution.

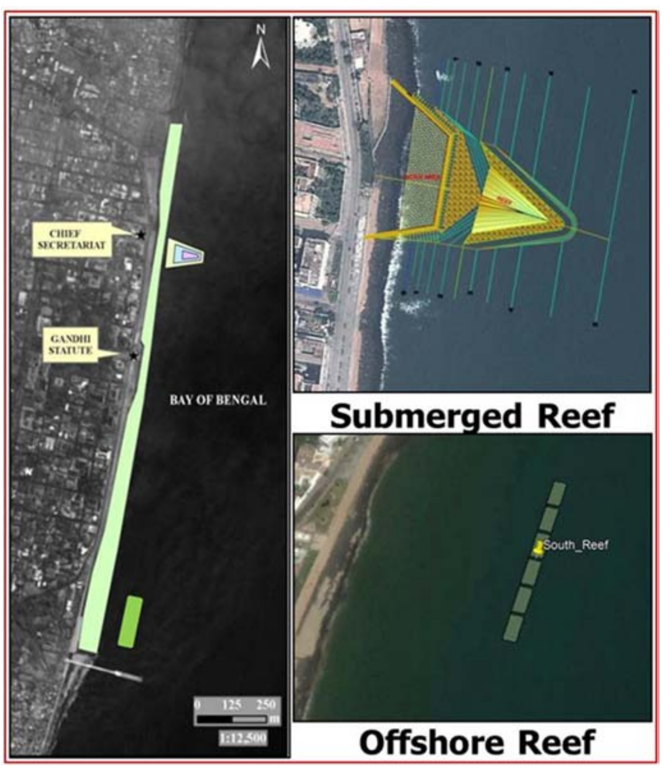


FIGURE 8

Construction of the northern reef.

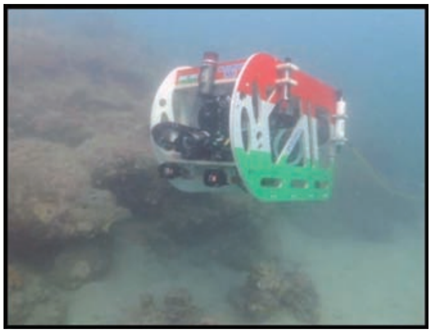
Coral Reef Monitoring

Corals are diverse shallow marine ecosystems that grow over geological time scales. They play an important role as a habitat for organisms in their environs supporting a vast diversity of animal and plant species. An increase of even 1–2°C above the monthly mean temperature could damage the symbiosis between the coral and zooxanthalle, leading to coral bleaching. During the last few decades, due to global warming, the genetic heritage of coral ecosystems has been reported to be at risk. Similar to the National Oceanic and Atmospheric Administration reef watch program, based on satellite data, INCOIS provides information on the early signs of increasing thermal intensity and the spatial extent of coral bleaching (INCOIS, 2017).

The corals of Andaman Island, which has the richest coral diversity

FIGURE 9

PROVe in South Andaman coral reef expedition.



among all Indian reefs, were victims of thermal stress due to the elevated temperatures that resulted in coral bleaching during 1998, 2002, 2005, and 2010. Coral reef surveys were conducted at the North Bay, Chidiyatapu, Jolly Buoy, Red Skin and Grub Islands of the south Andaman district using the NIOT-developed Polar/shallow remotely operated vehicle (PROVe) (Figure 9).

PROVe, with the underwater navigational aids and high-definition underwater cameras, was maneuvered in the coral reef habitats. High-resolution visuals of faunal assemblages, underwater spatiotemporal spectral irradiance characteristics, along with the surface radiance, water temperature, and salinity, were recorded (Figure 10). The observations revealed that most of the coral ecosystems are in the recovery stage resilient stage after major events such as the 2004 devastating tsunami and the bleaching events during 2005 and 2010. No bleaching signs were observed as water temperatures were within the temperature tolerance limit of the coral reef regions in other tropical oceans (Ramesh et al., 2017).

Marine Bioprospecting

Effective marine bioprospecting is essential for pursuing human health, offering a sustainable supply of high-quality food, and developing sustainable sources of energy alternatives to conventional hydrocarbons, new industrial products, and processes with low greenhouse gas emissions. At the same time, protection and management of the stressed marine environment has to be addressed. During 2016, the global retail value of certified seafood was about US$ 11.5 billion, and global wild catch and aquaculture production was 163 MT, with China, India, and Indonesia contributing 60%, 6%, and 6%, respectively. In the Indian Ocean Region, wild catch increased from 1 to 12 MT over the past six decades (Thompson et al., 2017). In India, efforts are undertaken to bridge the widening gap between the demand and supply of fish and to increase the production on par with other high-productivity nations. At the same time, in order to avoid overexploitation and to protect the ecosystem, INCOIS provides reliable and timely advisories on potential fish aggregation zones for the socioeconomic benefit of the fishing communities based on remotely sensed satellite data. Advisories are given to fishermen on a daily basis with specific references to more than 500 fish-landing centers along the Indian coast (ESSO-INCOIS, 2017).

In order to boost the fish aggregation methods based on engineering techniques, open-sea cages with mooring systems capable of withstanding turbulent seas are developed and demonstrated by culturing commercially important marine finfishes in different Indian sea conditions. The cages are made of high-density polyethylene with diameters larger than 9 m, and multipoint moorings were designed, developed, deployed, and tested by NIOT in the North Bay in the Andaman Islands, Olaikuda in Tamilnadu, and Kothachathram in Andhra Pradesh, representing fully protected, semiprotected, and open-sea environments, respectively (Figure 11). The cages have withstood even cyclonic weather conditions (NIOT, 2017).

Using these cages, the culture of several marine finfishes, such as the Asian seabass, cobia, pompano, milkfish, parrot fish, and giant travelly, was demonstrated. The milkfish seeds

FIGURE 10

View of resilient coral reef ecosystems (Ramesh et al., 2017).

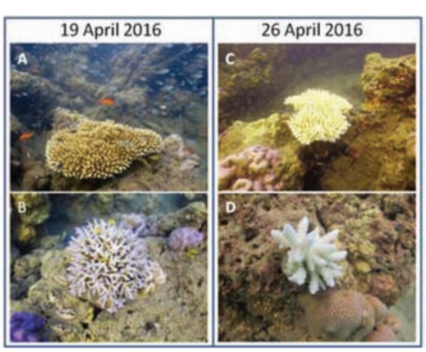
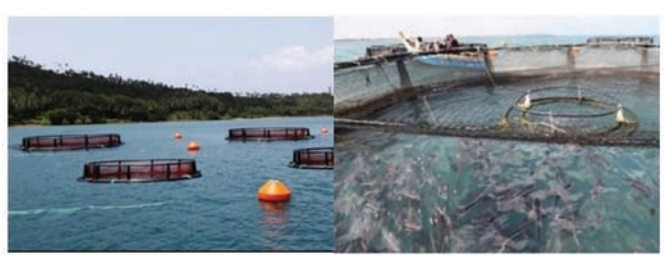


FIGURE 11

Open-sea cages in Andaman and Olaikuda.



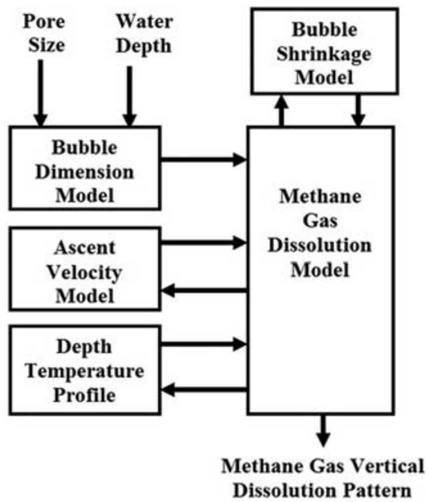
(5–8 g) were successfully reared to 770 g within 260 days in the open-sea cages at Okaikuda using a formulated diet. A total of 3.5 tons of milkfish was harvested. The culture of the hatchery produced marine finfishes, pompano, and the fast growing cobia were also successfully demonstrated with a total harvest of 3 tons in the sea cages at Olaikuda. An average body weight of 4 kg was achieved in 8 months in cobia from its initial stocking size of 30 g with a growth performance of 16.5 g/day. In order to minimize the huge investment for nursery rearing in land-based larval rearing systems, a concept of nursery rearing of marine finfish fingerlings in sea cages was also demonstrated for the first time using seabass seeds, sized from 6 to 24 g, within a period of 45 days, with a survival rate of 90% (NIOT, 2017).

Hydrocarbon Leak Studies

With increasing concerns about climate change, the increased exploitation of deep-ocean natural gas and interest in the exploitation of methane gas from deep-ocean natural gas hydrate deposits are receiving significant attention. Subsea methane gas releases can result during deep-ocean well drilling operations, well head completions, and also due to subsea equipment failures during production processes (Olsen & Skjetne, 2016). Performing a quantitative assessment of the dissolution pattern of methane gas bubbles released into the deep-ocean marine environment during a potential leak is important in order to understand the dissolution pattern of the rising methane bubble from the leak point, its contribution to atmospheric greenhouse gas budgets, and the effect of dissolving methane in terms of the dissolved oxygen for the

FIGURE 12

Architecture of the methane bubble dissolution model.



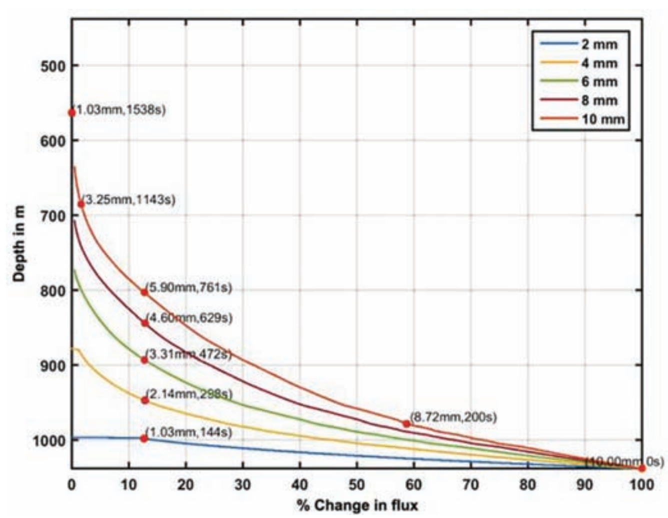
sustainability of biodiversity in the deep-ocean environment.

As the methane bubbles rise through the water column, methane exchange occurs between the ascending bubble and the ambient seawater, resulting in the dissolution of the methane. During the ascending process, the bubble size reduces due to dissolution, but the reducing hydrostatic pressure on the bubble causes it to expand. Hence, the bubble dissolution rate is determined by the depth of the bubble release and the extent to which the gas is transported upward. The solubility of the methane gas in the water column is governed by the sea water temperature, the surrounding fluid flow field, and the trajectory oscillations experienced by the bubble during the vertical ascent. Predicting the dissolution pattern of methane gas bubbles released in deep sea water within the hydrate stability field is further challenged by the potential formation of the hydrate envelope, allowing methane to reach relatively shallower depths. Precisely understanding and incorporating these physical and chemical processes involving dynamically changing ambient conditions into the bubble models are necessary to estimate hydrocarbon transport from the methane bubble leaks into the ocean water column.

A methane gas dissolution model is developed (Figure 12) for assessing the vertical dissolution profile of the methane gas as the bubble ascends through the water column. The simulation results represented (Figure 13) indicate

FIGURE 13

Bubble dissolution model studies in the Krishna-Godavari basin.



that methane bubbles with a diameter of 10 mm can transport methane gas to 650 m from the seabed in the Krishna Godavari basin on the east coast of India, where increased commercial exploitation is being planned. Results also indicate that about 50% of the molar mass of the released methane could get dissolved within 40 m of the water column from the seafloor (Vedachalam et al., 2017).

Conclusion

With the upcoming integrated approach, the blue economy is expected to serve as a growth catalyst for a robust Indian economy envisioned to reach US$10 billion by 2032. As discussed, with the exploitation of ocean resources on the uptrend, the technologies developed for coastal protection, cyclone and tsunami early warning systems, coral habitat observations, sustainable fishing, and numerical studies on the deep-ocean natural gas well head leaks are all essential to the Indian economy, and it is critical to keep these economic activities in balance with the long-term capacity of ocean ecosystems in the Indian seas and oceans.

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PAPER

New Dynamic Positioning Reference System Concepts Enabled by Autonomy

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ABSTRACT

A certain level of autonomy is already present in dynamic positioning (DP), and DP requirements have been a driving force in the development of a diversity of high-reliability reference systems. Today, there is a strong drive for autonomous concepts and solutions in several market niches (e.g., short sea shipping and ocean-based aquaculture). At the same time, the market downturn in traditional oil and gas leads to a reduced implementation of new reference system solutions. A development toward higher levels of autonomy in novel operations drives the development from traditional reference systems toward solutions capable of proximity awareness and connectivity. The existing reference system technologies comprise a good platform for this development, but new technology elements like new sensor fusion concepts, machine learning, artificial intelligence, and extended connectivity are evolving. The article presents ongoing developments within microwave, laser, Global Navigation Satellite System (GNSS), and inertial-based reference systems and discusses likely future developments. Connectivity will be a native feature of future reference systems and is also discussed. The article is focusing on the drivers behind these developments and some of the related challenges from a high-level perspective. Current development is running at a much higher pace than legislation and regulation can adapt. Some input to regulation challenges and trade-offs are outlined.

Keywords: autonomy, dynamic positioning, sensors, sensor fusion, proximity awareness

Introduction

Dynamic positioning (DP) is an automated system controlling the heading and position of a vessel by using thrusters and propellers. Position reference systems, wind sensors, motion sensors, and gyrocompasses provide input to DP to combine information about actual heading and position and the magnitude and direction of environmental forces affecting the vessel's movements. DP uses a mathematical model of the vessel and combines this with sensor input to calculate the appropriate steering signals to individual thrusters. DP may keep the position relative to either a fixed position or a moving object like another ship.

Autonomy

Autonomy is about systems that can operate independently with a varying degree of human intervention. There are many definitions of different levels of autonomy, but it is important to note that autonomy does not necessarily mean unmanned. Autonomy is achieved by using technology elements like algorithms, software, hardware, interaction with humans, and legislation. With a low degree of autonomy, humans manually control all actions, but with a high level of autonomy, systems make decisions and carry out actions with the human in a monitoring and supervisory role.

Autonomy involves a range of interested parties and elements including the following:

- Vessel
- Mission
- Developer
- Project manager
- Commander
- Management
- Society

Autonomy is, in other words, about a lot more than technology even if technology provides enablers for autonomy.

The most important technologies comprising enablers for autonomy are the following:

- Sensors for measuring surroundings and conditions
- Perception for analysis of signals and data generating proximity awareness
- Communication for interaction and meeting security challenges
- Cognition for planning, learning, and adaptation
- Localization and mapping relative to the operating environment
- Human-machine interaction for remote monitoring or control and to keep humans in the loop

The development within many of these technology areas is moving very quickly due to strong technological advancements toward autonomy within driverless cars. It is still important to be aware that autonomy in the maritime domain in many aspects is different from road- and land-based autonomy. The maritime domain will benefit from the development of driverless cars but will also require unique and different solutions.

DP and Autonomy

DP already includes a set of autonomous functions that have been around since the 1960s. Under normal conditions, the DP operator can leave the maneuvering of the ship to computers and machinery in most situations but has the opportunity to intervene when the technology reaches its limits. In such situations, it can be questioned if the operator also meets his or her limitations and the value of such human intervention may be questionable (Figure 1).

DP uses input from several sensors and reference systems to replace and improve the senses of the operator. DP uses sensor fusion to obtain a picture of what is going on and the kinds of forces that are affecting the vessel before power is allocated to the thrusters. To avoid propagation of errors from the reference systems to the power allocation, it is usually required to use at least three reference systems simultaneously, where at least two should be based on different measurement principles according to class regulations.

New Operational Concepts

There are strong drivers for moving transport from roads to sea and strong ambitions to develop more cost-effective solutions for maritime operations. To reach these ambitions and be able to develop new solutions, the cost levels need to be reduced. Combining strong drivers and development of enabling technology, several new operational concepts are pointing to a future where even more activity will take place at sea or on the oceans. A few domains driving new operational concepts are the following:

- Offshore wind park operations
- Exposed aquaculture
- Coastal transportation

These domains represent first-mover opportunities that can potentially lead to full-scale developments of radically new solutions, like, for example, the Yara Birkeland zero-emission container feeder. Even if traditional solutions exist for decades, it is foreseen that solutions developed to reach the ambitions of these projects will flow into traditional operations (Figure 2).

Proximity Awareness

Traditional DP reference systems usually provide position measurements relative to earth-centered or relative coordinates in X, Y, or Z or as range/bearing measurements. The traditional reference systems have limited capabilities of handling noncooperative targets. Even if some capability of lever arm compensation is provided, they have limited capacity of representing the positions of the entire hull for collision avoidance or optimal maneuvering.

Vessels with a higher level of autonomy require features exceeding those provided by current reference systems, to provide significantly better proximity awareness compared to what is available today. DP will need to relate to activities going on the vicinity of the vessel to be able to maneuver efficiently.

FIGURE 1

Maneuvering by using DP.

FIGURE 2

Yara Birkeland—zero-emission container feeder.

There is a massive development within the automotive industry toward driverless cars, and it is expected that new solutions can be transferred from automotive into other domains. It is both inspiring and interesting to look at sensors and sensor integration in a modern car in order to get an impression of the functionality that is used. At the same time, it is important to be aware of the differences between the automotive domain and the maritime domain.

There are some important differences between a modern car and a vessel operating in a maritime environment:

- The size and variation in size of vehicles—it is questionable if it will be possible to equip a ship with the same density of sensors per meter as in a modern car.
- The environment—weather conditions are expected to be worse in a maritime environment than on roads.
- The inertias involved in a maritime operation limit the maneuverability of the vessels.
- At sea, it is usually not possible to pull over and stop if something goes wrong.

The list is not complete but points at some major differences between road and maritime applications. These are influencing technology requirements and solutions that make it difficult to directly transfer solutions from one application to another.

Solutions for higher levels of autonomy also require connectivity to be addressed in a more comprehensive way. Sensors and systems need better interaction onboard, but digital communication channels also need to be available for ad hoc connection between vessels involved in the same operations or operating in the vicinity of each other. It is also necessary to reconsider traditional solutions for connectivity between sea-going vessels and land-based infrastructure.

Technology Developments Within DP Reference Systems

DP reference systems based on microwave signals, usually in the 5- or 10-GHz bands, are well known. Modern, solid-state technology makes it possible to improve the performance of such systems to avoid moving parts and increase the resolution and accuracy of current solutions.

Phased array antennas and powerful signal processing are important features of this technology. Systems can consist of active nodes for extended range and accuracy or the combination of active and passive nodes or even provide radar-type images for proximity awareness as well as detection and identification of noncooperative objects.

There are new ongoing developments of lasers operating in the infrared band (one 550-nm wavelength), making it possible to provide long-range LIght Detection And Ranging (LIDAR) functionality required in maritime operations with night vision capabilities. LIDARs are essential in autonomous cars, but the range and visibility requirements are much stricter in maritime environments.

The deployment of new navigation satellites in the four global constellations—GPS (United States), Galileo (Europe), Glonass (Russia), and Beidou (China)—has been increasing over the last few years. Today, there is a total number of about 100 such satellites in orbit.

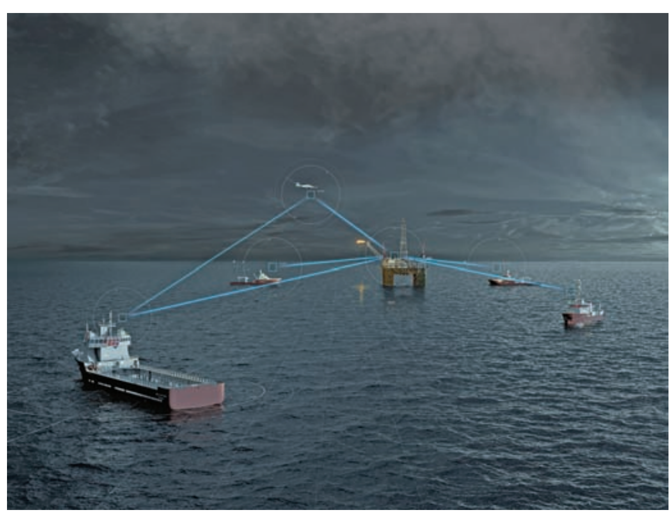
The use of inertial solutions is increasing and also the development of new solutions, which provide north-seeking capabilities and inertial navigation performance. There is a trend toward integration between GNSS and inertial solutions to reduce the need for costly differential solutions even in some DP operations. Solutions for real-time transfer of attitude data between vessels are emerging, for example, relative heave compensation between vessels (Figure 3).

Fusion and Beyond

As mentioned earlier, sensor fusion has been used in DP for decades.

FIGURE 3

Maritime connectivity—essential in autonomous operations.



Fusionof different reference system technologies such as GNSS and inertial measurements is also well known.

Autonomy requires fusion to take place at a completely new scale compared to traditional DP and DP reference systems in order to achieve true proximity awareness. Data-driven methods like machine learning are already used in the development of driverless cars, and these technologies are available for maritime applications. Data-driven methods are well known in science, but using large amounts of data and powerful processing of these data give new opportunities to traditional maritime operations. Machine learning techniques can be used to recognize, identify, classify, comprehend, learn, predict, decide, and act in an autonomous operation.

One large concern related to machine learning is the black box problem. It is hard to really know what is going on in a machine learning process. It is also hard to know if the data set used to train the machine learning algorithm is representative and faultless. These challenges need to be addressed, especially in safety critical applications and by regulations and legislation. Machine learning is usually associated with artificial intelligence. It is worth noting that artificial intelligence, like human intelligence, can fail.

Another development enabled by Moore's law (the exponential growth of number of transistors per square millimeters of silicon) is the possibility to solve computer-intensive tasks closer to the data source or the sensors, which is known as edge computing. It is even possible to use the increasing processing power of the sensor, or networks of sensors, to make computations usually belonging to centralized computers. Machine learning and sensor fusion do not necessarily require more processing capacity of the centralized computer system but might be solved directly in the sensor network.

Sensor fusion at a level required by autonomy also requires a comprehensive platform for massive processing and rapid deployment of new algorithms and solutions. A typical platform task is to provide a consistent platform for cybersecurity as connectivity increases and the opportunity for manual intervention is reduced. Advanced analytics of huge amounts of data also require access to the combined processing power of large processing and storage plants to, for example, train machine learning algorithms.

Regulation and Legislation Challenges

The challenges to regulations and legislation are huge because of the rapid technology development and the development of completely new, full-scale concepts. Regulations and legislation are not expected to drive the development, but it is important to change the pace of the regulatory and legislation work.

Even if technology is changing rapidly, the fundamental trade-offs between different performance parameters still apply. These trade-offs cannot necessarily be derived from existing applications and operations into new, autonomous applications. It is necessary to carefully analyze the basic, operational requirements and derive a new set of operation-specific requirements. It is also necessary to collect data at an early stage in the development cycle to be able to verify new solutions and approaches.

The development of digital models of vessels and simulations can be a valuable tool in this work. A digital twin of a new concept can potentially be developed much faster than the physical construction of a new vessel.

Conclusion

The development toward a higher level of autonomy in maritime operations and the development of new operational concepts are potentially a game changer for DP operations. Technology and solutions are expected to flow from the new concepts into more traditional applications. New concepts are drivers, and technology seems to be an enabler.

Sensing, connectivity, and computing are core elements in this development, and the features provided by new solutions can increase efficiency, reduce costs, and increase safety. This development will eventually feed back into the development of even better and more versatile sensors.

The opportunities in data-driven methods such as machine learning will enable new levels of sensor fusion, but it is important to address the pitfalls of these technologies, especially in safety critical operations.

The rapid development of new concepts and technology comprises substantial challenges to regulations and legislation, but technology also offers tools that should be considered in these processes.

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PAPER

Cybersecurity: A Deep Dive Into the Abyss

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ABSTRACT

Cyberspace reaches all corners of human access and includes cyber-physical systems such as power grids, communication networks, industrial plants, transportation networks, ports and shipping, and a myriad of networked home appliances through the Internet of Things. One goal of this article is to engage and inform personnel in the maritime domain to help secure cyberspace from adversaries. Another goal is to provide an introductory systems view to help manage cyberspace security. We show that cyberspace is a reflection of human networks and share the advantages and flaws inherent in these human networks. Trust in this network is the missing link that prevents us from securing this network. Although this viewpoint is not an exact model, we believe it helps simplify the complexity of cyberspace and the wide variety of attacks that are possible. These goals help the average person see the big picture, and the entire system can become more robust by allowing everyone to participate intelligently in this endeavor. This article explains in a more simplistic but useful manner the domain of cyberspace, enabling better security of the ecosystem.

Keywords: cybersecurity, maritime, systems, networks, trust

Introduction

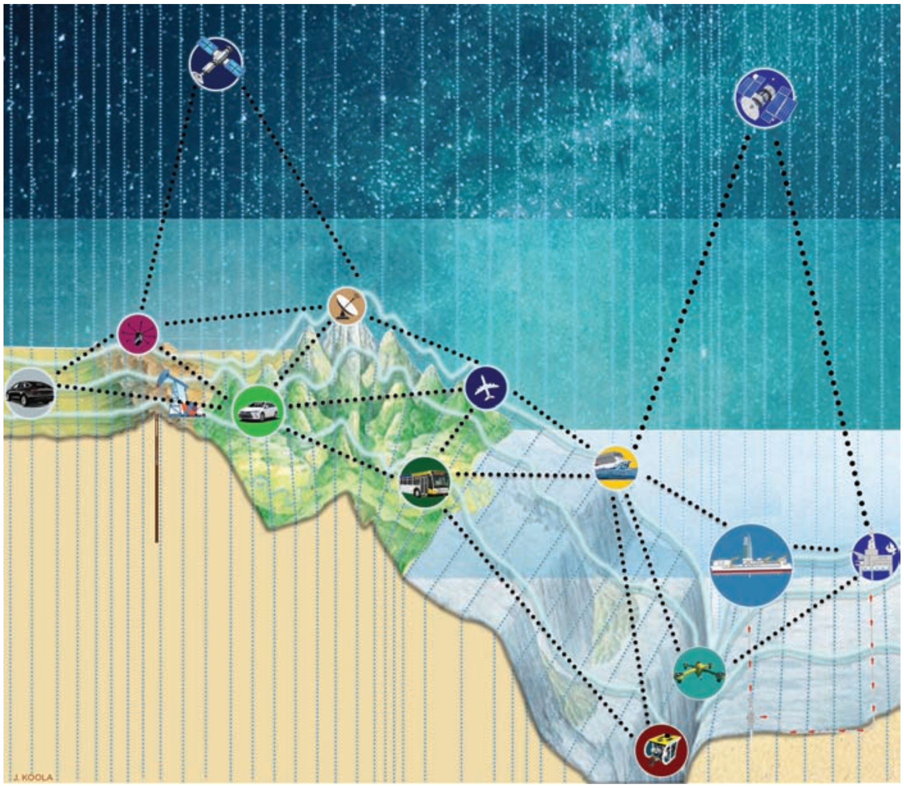
To understand the complexity and issues associated with cybersecurity, one must be knowledgeable about the evolution and growth of cyberspace. Cyberspace reaches all corners of human access, and for this article, it groups all interconnected devices into one large virtual space (Figure 1). Cyberspace encompasses cyber-physical systems such as power grids, communication networks, industrial plants, transportation networks, ports and shipping, and a myriad of networked home appliances through the Internet of Things (IoT). One goal of this article is to engage and inform the average user in the maritime domain to help secure cyberspace. Maritime shipping moves 90–94% of world trade (Walsh, 2015). Cyberspace in the maritime domain encompasses ports and harbors, shipping, offshore facilities, and autonomous ships and the satellites that keep these systems connected to the deepest depths of the ocean where autonomous underwater vehicles navigate.

Cyberspace is a complex, adaptive, networked system created by humans to enable information exchange across space and time. It consists of computational nodes and communication lines connecting these nodes. Internode communication has grown explosively since the birth of the Internet. Cyberspace is in its next growth cycle with the evolution of the IoT and high-speed wireless connectivity. Although cyberspace originally consisted of computer networks enabled with electromagnetic communications, IoT has enhanced this network with sensors and actuators capable of continuously monitoring and manipulating the environment we live in, transforming it into an ecosystem that has a life of its own. Given the pervasiveness of smartphones and other voice-activated gadgets integrated into this cyber network, the DNA of this network has human behavior in-built into it. Currently, we are in the era of man-machine symbiosis. Our societal push toward autonomous vehicles and the resulting expansion into the oceans is accelerating the rate at which the entire globe will become instrumented, automated, and interconnected, giving us a first look at real-time vision into every nook and corner. Acoustic communication with underwater robots will further expand the electromagnetic medium to the acoustic medium and thereby extend our network reach. This complex adaptive system has life-like behaviors due to dynamic manipulation of the nodes of this network by us humans. Cyberspace is mostly unregulated and uncontrolled. We need to ensure that this system will not trigger unwanted consequences for the planet we live in, in this Anthropocene Age. We need to study this system more in depth, across all interconnected domains. The second goal of this article is to understand the fundamental systems that manage the security of cyberspace and each person's role within these systems.

To understand this human-engineered cyberspace a little better, we might want to step back and look at the evolution of communication and computational brainpower

FIGURE 1

Cyber network—A deep dive.



in the human species. Humans communicating using auditory, visual, and tactile stimuli evolved to optimize language, the cognitive ability to learn and use complex communication. This advancement supported the ability to form a theory of other minds and shared intentionality (Tomasello, 1996; Hauser et al., 2002). Our brain volume expanded during this period of language perfection. Our human brain's metabolic requirements peak in childhood when it uses glucose at a rate equivalent to 66% of the body's resting metabolism and 43% of the body's daily energy requirement (Kuzawa et al., 2014). This brain growth further enhanced language development. The transition from a nomadic hunter-gatherer civilization to an agricultural civilization where collective security was ensured accelerated brain development for complex language and abstract thought processes.

The two key points to note are the increase in communication complexity and computational power of the brain. This first human communication network has served our species well. We have evolved from tribes into societies and have dominated the planet. Individually we are not the strongest or largest species, but as a collective whole, we have taken over this planet. Social insects like ants, though they collaborate well, do not have the computational power at the node as we do. The combination of powerful computational nodes with high bandwidth communication is a dominant paradigm. Cyberspace is a reflection of this network with powerful redundant nodes and high bandwidth communications. Redundancy is an essential criterion for robustness of the system as a whole. The human species is dominant not because each node consisting of us mortal humans lives forever but because we reproduce new nodes that are more knowledgeable and powerful. These human networks or civilizations grow more potent as a holistic system until catastrophic conditions bring about the fall of civilizations. Cyberspace has pushed the limits of these human networks using communication channels that now span the globe and into space using the interplanetary Internet (Jackson, 2005). We need to ensure that these interconnected cyber networks that we have engineered survive the test of time.

As these cyberspace networks grow in size and power, trust between nodes has become an issue. When we operated in small networks such as tribes, the chief knew and trusted all human nodes, and nodes that were not reliable were eliminated. The removal of some nodes maintained the integrity of the tribes. As tribes became societies and the network grew, new structures had to be put in place like formal laws and courts to eliminate adverse behavior to control chaos and maintain the stability of the system. When people networks expanded to computer networks with humans controlling these nodes, we did not create a decent enough system to deal with trust at the nodes. The Internet communication protocol was designed to propagate information from node to node irrespective of the damage to the other nodes in the network. As long as there is one path open between the two communicating nodes, the message will be passed, though there is no guarantee on the time it would take. Then communication was assumed to be between trusted parties, and hence, security was not a design intent. Cybersecurity issues we see today are due to the lack of trust between nodes. Metaphorically, the three-legged stool is weak on the third and critical leg of trust. The other two legs, node intelligence and high bandwidth communication links, are not sufficient to maintain and manage a stable and healthy cyberspace. In short, as the network expands in size, trust in the system is essential for proper operation. Given this framework, we will explore how best we can manage the current situation.

Complex Adaptive Systems

Cyberspace is a complex adaptive system, which has interactions linking individually based microprocesses at the nodes to macrosocial outcomes at the network level. In such a system, even a perfect understanding of the individual parts does not automatically convey an ideal knowledge of the system's combined total behavior (Miller & Page, 2007). These networks have self-organization capabilities and self-similarities like fractals. Flaws at the local nodes can replicate and produce emergent behavior at the global level. These facts will help us engineer the system better, both at the micro and macro levels. To help us understand these systems, we shall discuss common systems that might give us a frame of reference to fathom the complexity of cyberspace.

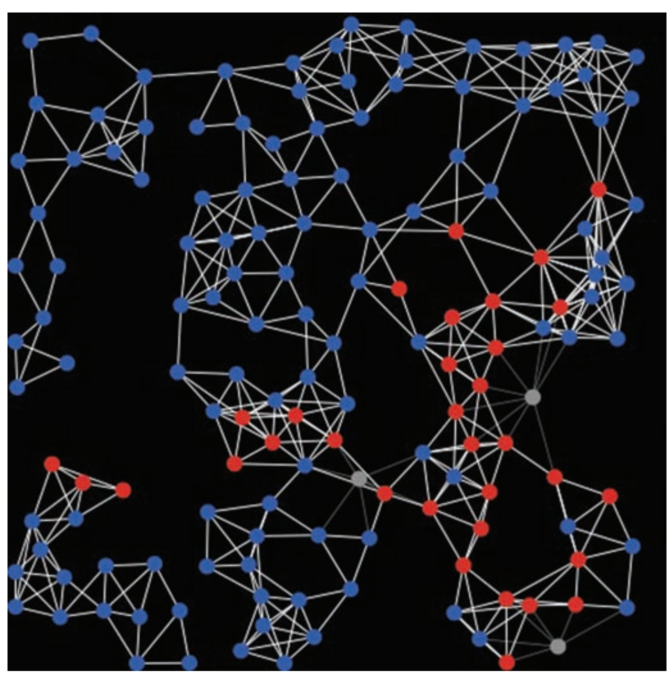
First, let us look at external factors threatening complex adaptive systems and see how we can learn and adapt from them. The human body is a complex network of organs all functioning and working together to produce a holistic system. Sometimes things go wrong, and some nodes or organs will degrade or fail. As long as the organ failure does not propagate to other organs and we can replace that failing organ or if the organ has built-in redundancy, the system survives. Spread of a disease like cancer across the network is dangerous when nearby organs collapse due to infection propagation and the system does not survive. We hope the entire cyberspace will not collapse even though, inevitably, a small percentage of the nodes will be compromised at any given time.

A different but less critical analogous model is the spread of disease like flu across the human population as studied in epidemiology. Vaccination as a mechanism to prevent the spread of the disease-causing bacteria or virus (Honner, 2018) has an analog on a computer network similar to an antivirus software deployed on the network's node machines. These network effects modeled at the global system level and the impact of virus propagation are studied based on three states, Susceptible, Infected, or Resistant, referred to as an SIR model for epidemics (Stonedahl & Wilensky, 2008). Figure 2 shows a system-level simulation model of virus propagation. These high-level simulation models can span across domains from disease propagation to computer virus spread and help us understand and operate these systems better.

Knowledge replication across domains and the power of abstraction is what differentiates our intelligence from other species. Although these higher-level systems tools help us understand emergent properties of cyberspace, we must dig deeper into the subsystems to help protect the cyberspace we have engineered. The subsystem behaviors at the nodes when aggregated produce the emergent properties at the systems level.

FIGURE 2

Virus on a network (Stonedahl & Wilensky, 2008).



It is hence useful to understand the subsystem nodes in more detail.

Nodes in the Network

Just as every node on the human network is an intelligent human, we can model every generic cyberspace node as an intelligent computation and control device with sensors and actuators. The human brain is the computational mechanism, our five senses—sight, touch, hearing, taste, and smell—are the sensors, and our limbs are the actuators. The IoT node in cyberspace is a close replica, analogous to the human node on the human network. Not all nodes on the cyberspace network need to have all the capabilities of sensing, actuating, or even computation. In cyberspace, computation at the nodes uses sensor feedback to control actuators and is analogous to the human body where the brain uses the senses networked together to control our limbs. In this article, we will abstract every node to have computation and control capabilities if so desired.

Given this abstraction, we can further reduce the subsystem node to a stack of components layered one on top of another. To keep matters simple and for this article, our computational and control node will consist of high-level components where we can study security in more depth. This computational and control node comprises the hardware, operating system (OS), and application software sitting on top of the OS. We can add sensors and actuators as additional components to the computational and control stack if so desired without loss of generality. The sensors measure the environment, and the actuators react to the environment based on the computation and control at the node. The sensors and actuators need not be at every node but could be distributed across the network and made accessible to a variety of nodes using smart transducer standards like IEEE 1451.X. (Song & Lee, 2008).

The nodes that are connected by communication pipes can be sending, receiving, or both. Usually a sensor node will be sending out signals, but with modern smart transducers, a sensor can receive input request and change the data characteristics it sends out based on these input requests. Similarly, an actuator node will respond to control stimuli, but new smart transducers can have built-in memory and computation on board that enables the device to behave in intelligent ways based on predetermined policy and prescribed logic. These policies can also be changed in real time remotely based on data and artificial intelligence (AI) algorithms. This dynamic feature exposes the system to the possibility of hackers making these policy changes either manually or using AI software, hence the possibility of newer attack vectors on these devices.

Depending on the functionality, these nodes are sometimes classified as clients or servers. A node that produces information is a server, and one that consumes information is a client. In bidirectional networks, both nodes could act as clients and servers. In a telephone or video call with multiple parties connected, all nodes act as client and server. A GPS satellite for consumer applications is a server, whereas the GPS device is a client. A GPS satellite can be degraded for defense applications, and it then acts as a client receiving inputs. In general, as the node is more capable and more complex, there is potential for more flaws. We have to manage security flaws for this explosion of capability.

Network Communications

Just as the nervous system in our body connects our brain to the various senses, we need channels of communication wired or wireless to connect the different nodes in cyberspace. Human senses communicate with nerves wired through our body to the skin for touch and tongue for taste and wirelessly through acoustic speech for hearing, electromagnetic visible spectrum for sight, and chemical scent through the nose for smell.

Electronic communication started with the telegraph, a digital system used to transmit dots and dashes, which maps to the text in the language. Then came the telephone, which uses acoustic voice converted to analog electrical signal riding on a carrier wave through wires. Later came the wireless radio transmission through electromagnetic waves. We now have information transfer wired through cable and fiber and wireless through multiple standards such as WiFi, Bluetooth, and cellular such as 5G.

Drums used in tribes and horns on ships are also a way of communication. In marine networks, underwater acoustic communications are also used in addition to the conventional electrical communication technologies. The key takeaways in communications are that there are different physical channels wired or wireless and communication transfer signals electric, electromagnetic, or acoustic. Touch and smell are also possible. Various combinations of physical channel and communication signals are possible such as electric through metal, electromagnetic through the fiber, acoustic through air or water, and electromagnetic through space, to cite a few. All these communication technologies can be intercepted and tampered. Hence, these channels are injection points that could reduce trust in the system.

Network channels could be encrypted, thereby providing confidentiality of message passing. Encryption could also be used to ensure the authenticity and integrity of the source of the message. Finally, availability of the message has to be guaranteed by preventing adversaries from choking the communication channels using denial of service attacks. These three, confidentiality of information, the integrity of information, and availability of information, are in network parlance called the *CIA triad* and are used as a framework to ensure secure communications.

A recent development in information transfer using quantum communication, which has the desirable property of protecting information channels against eavesdropping using quantum cryptography, might come to our rescue in securing information transfer during transmission. These technologies will alleviate some of the problems of trust, which we discussed as the missing leg of our three-legged stool.

Now that we have a base understanding of the nodes in the network and the communication channels connecting them and understand that lack of trust in this system is the reason for cyber attacks, we can study how to defend against some of these attacks.

Defending Against Cyber Attacks

Malware Types

Some of the well-known malware and their signature are listed below:

- The virus is an executable type of malware that self-replicates by infecting original code by injecting code fragments.
- Spyware is a piece of software that covertly collects, tracks, or steals user's sensitive data by installing itself on to a machine.
- Trojan hides in a legitimate program and steals sensitive information by misleading a user to give it privileged access.
- Rootkit gains access to machine OS, conceals itself or other malware, and is capable of executing files and also making changes to the system.
- Ransomware encrypts a user's data on their machine and will unencrypt their data only if the user pays a ransom. If not, the data will be deleted or released online.
- Worms can replicate and automatically spread to other machines.

Although this list is not complete and will keep growing and evolving, the signature of these malware types should give the user a quick summary of the primary chosen means of attack and propagation behaviors. Figure 3 shows the most costly malware outbreaks of all time (Martindale, 2018).

Attack Vectors

The critical parameters for disease or fault propagation in the networked system as a whole depend on these three factors: Susceptible, Infected, or Resistant (SIR) (Stonedahl & Wilensky, 2008). Given our goal of studying cybersecurity, we can use this SIR model and the taxonomy of cyber attacks to understand the effect of these attack vectors better. One way to think about this is to study the attack vectors and then decide if it is capable of infecting a node or if the node is susceptible given other additional conditions. One can also study if the node is resistant to attack given its current set of defense postures. A partial list of the taxonomy of cyber attacks is shown in Table 1 (Simmons et al., 2014). New attacks will continue to grow and new defense mechanisms will have to be engineered as part of a never-ending game.

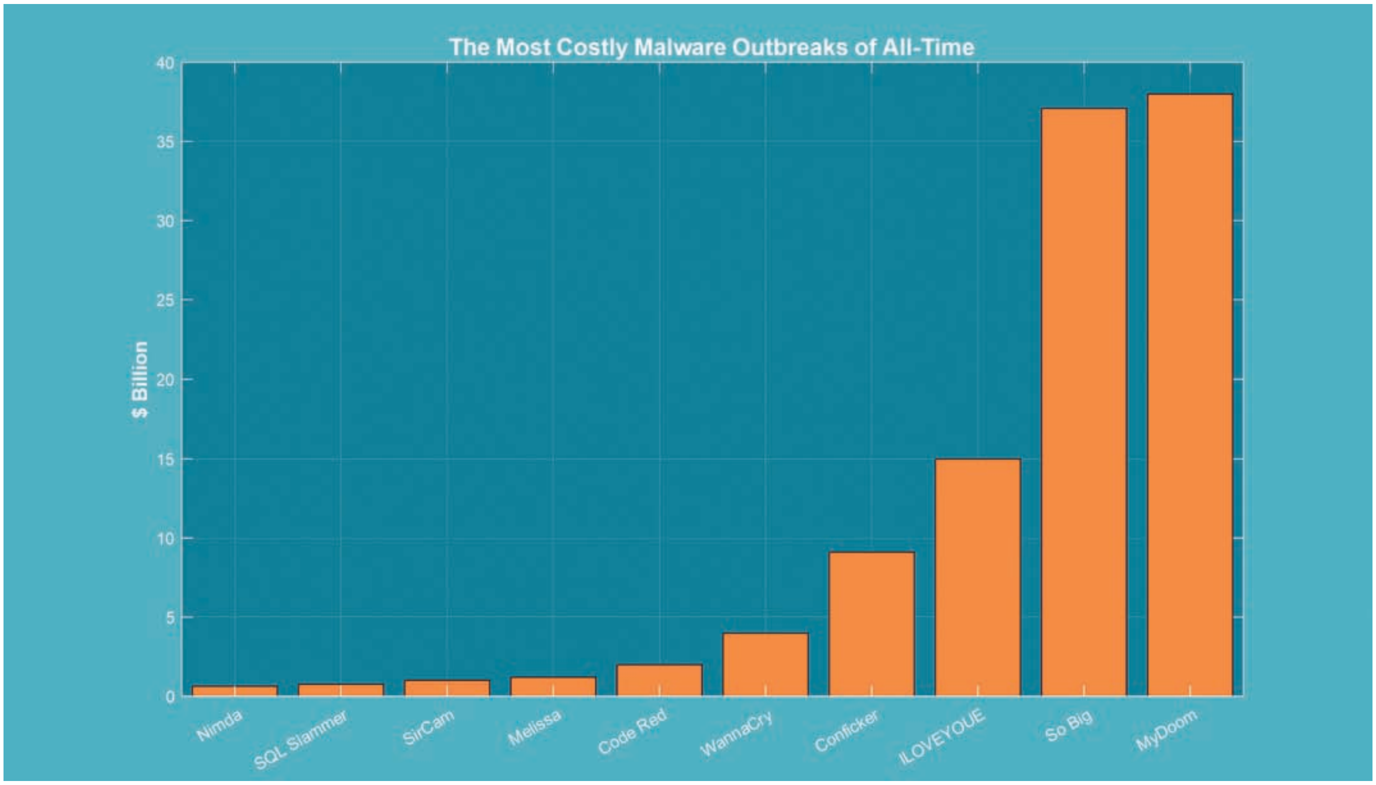
If we look at the targets, we see the breakdown of the stack we listed earlier. Local machine refers to hardware, OS Kernel, the OS, and users and application associated with the application software. Also, we have the network connecting these nodes where information could be manipulated or even pried upon as discussed in the network communication section above.

These targets are identified by specific flaws inherent in the system as seen in the attack vectors column in Table 1. Kernel flaws are issues related to OS design. Design flaws can be at the hardware, OS, or application software level. As can be seen, design flaws could already encompass OS flaws. There could be OS flaws not related to design but manufacture. It is this overlap and lack of rigid boundaries in specifying classes of flaws that make dealing with cybersecurity very complicated.

Buffer overflows are memory leakage that happens when memory bounds are not checked before writing into memory. We will revisit this later in the security section. A buffer overflow can be prevented at the hardware level, OS level, or even application software level. Incorrect permissions are what allow someone without authorization to access data that can be used to manipulate the system. Accessing restricted data happens by using flaws at the application

FIGURE 3

The most costly malware outbreaks of all time (Martindale, 2018).



software level to gain permission at the OS level.

Social engineering is the result of having humans interact with themselves and the nodes of the network. A common theme here is to trick the user into giving out passwords, thereby allowing the perpetrator to act as a different user with a different set of permissions.

These are some possible attack vectors. The intent is to give the reader a flavor of the diversity of attack possibilities. As we keep breaking down these attack vectors, we see more and more hybrid attacks happening across the hardware-software network stack. The more complex the attack, the

TABLE 1

Taxonomy of cyber attacks (Simmons et al., 2014).

Attack Vectors	Operational Impact	Defense	Informational Impact	Target
• Kernel flaws • Design flaws • Buffer overflows • Incorrect permission • Social engineering	• Compromise ○ Root ○ User ○ Web • Malware installed ○ Virus ○ Spyware ○ Trojan ○ Worm • Denial of service ○ Host ○ Network ○ Distributed	• Mitigation ○ Remove ○ Whitelisting • Remediation ○ Patch ○ Correct code	• Distort • Disrupt • Destruct • Disclose • Discover	• OS Kernel • Network • Local m/c • User • Application

more difficult it is to defend against it. We can understand this better by looking at the operational impact of these attacks.

The first strategy to carry out high-impact damage to the system is to compromise the system components such as root (OS), user, or web application. Compromising the root gives control over the machine. Compromising the user account gains access to most devices the user account has access to. Compromising a web application provides access to most users associated with that application. This first step looks like a recruiting stage gaining control over multiple users and machines. Once compromised, all assets under malicious control are then infected with malware.

These rogue programs sitting on assets under the adversary's control can then be used to produce a denial of service attack on either the host or the network. When done in synchronization, simultaneous attacks can cause distributed denial of service, and a significant portion of cyberspace can be made nonfunctional, creating massive consequences depending on the target. A cyber-physical system attack such as on the electric grid or water supply will wreak havoc on society when taken down.

Ordinarily, remedial measures are implemented after the attack is visibly discovered and the crime has done detectable damage. So how do we recover or better prevent these attacks? Recovery procedures involve detecting and cleaning infected files from all components of the system. A proactive measure is to use software that can identify and clear instances of these rogue programs. One strategy is to look for signatures of past malware and prevent them from taking over our systems. We described simple attack vectors and strategies above. Strategies that are more complex are discussed below.

Higher-Order and Side Channel Attacks

There are categories of attack vectors not listed in Table 1. The first one is higher-order attacks. It is easier to explain a higher-order attack using an example. Assuming that system penetration is not caught immediately, the adversary decides not to damage computer systems but alter processes that could then lead to catastrophic failure. As an example, let us assume that a malicious actor can change the algorithm that stacks containers on a ship. Can the malicious actor then stack the shipping containers using the modified algorithm such that the vessel becomes top heavy and collapse under the moderately severe weather? This kind of higher-order attack is more difficult to detect. If we were to track patterns of container stacking, then such an anomaly can be caught similar to credit card fraud detection. Thinking through these tactics is not the normal first line of defense mechanism, but we need to look out for such patterns as attacks are getting more sophisticated.

Side channel attacks use acoustic or electromagnetic signals leakages to give away the secret key during encryption. Imagine listening in to keyboard typing to gain access to passwords. These are more difficult to protect against, as there are no traces recorded. The adversary can use the microphone or webcam of the user's machine without their knowledge, and it is challenging to protect against such an attack. The best way to stop this is signal acquisition detected by external means. Another alternative is to physically shut off the image feed to the camera lens or disconnect the microphone.

Implications

Currently, this is a cat-and-mouse game between the malicious actors and the cyber defenders—those who try and protect our cyberinfrastructure for the benefit of society. Most nodes in cyberspace are human controlled, and hence, cyberspace behavior is a reflection of the human behavior as seen in society. Given this fact, bad actors will always exist. The goal should be to accept this fact and reduce the damage that can be produced by these bad actors. To come out winning in this never-ending game, we should educate the masses to help make cyberspace more resilient. Good secure cyberspace design by itself might not be sufficient.

What is scary is that cyberspace is so vital to society and its functioning that nation-states have used it as a platform in modern-day cyber warfare. This cyber warfare behavior puts enormous funding and resources into malicious behavior, and new, unimaginable attack vectors are surfacing. One of the issues with these newly developed cyber weapons is that, unlike physical weapons that take considerable resources to duplicate like an aircraft carrier or a fighter jet, cyber weapon code once exposed can be replicated for minimal cost, leaving it in the hands of other malicious users that can cause more downstream havoc. Some of these malicious actors would produce destruction without financial return. Society needs to curtail this adverse behavior. We should manage this behavior wisely if we need to survive as a species. The

Anthropocene Age might result in our extinction and maybe all species. One of the ways society deals with this is by laws and policies. The pace of new cyber-attack strategies is evolving so fast that laws and policies are lagging behind. The speed of evolution is true of AI-directed technologies in general, and hence, the ethics of such warfare has to be intelligently studied due to the potential disruption to civilian life.

Threat Actors

Although it is impossible to categorize threat actors completely, it is helpful to know some popularly classified groups based on intent. As mentioned, because attacks are part of social behavior, this categorization helps us plan for defense mechanisms appropriate to each.

- Cybercriminals are those whose primary motivation is money, so they will attack if they can profit. These criminals are also known as black hat hackers, who will illegally exploit vulnerabilities and tell others how to do so. Hacker is someone with a deeper understanding of computer systems, and a cracker better denotes a malicious actor.
- White hat hacker will exploit vulnerabilities only with permission and not divulge its existence until flaws are fixed.
- Gray hat hackers are looking to profit from finding and exposing flaws and exploits in network systems and devices. They might violate laws or ethical standards but do not have the malicious intent of black hats.
- Script kiddies are usually amateur criminals who are driven by the desire for notoriety. Sometimes, however, they can help security researchers find and close security vulnerabilities.
- Hacktivists are those who want to undermine our reputation or destabilize our operations. Vandalism is their preferred means of attack.
- Nation state-sponsored attackers are after information for the long haul. They are well funded, use sophisticated techniques, and are in general difficult to identify until a catastrophe happens. Their attacks are referred to as advanced persistent threats.
- Insider threats are well-meaning people in the organization led astray, or they could be intentionally malicious due to some grudge.
- Internal user error is caused by regular employees making mistakes with configuration privileges they should not have. These errors have been known to bring down critical resources such as firewalls, routers, and servers, causing widespread or departmental company outages.

Principles to Secure Cyberspace

Given the scenarios described above, we may want to reevaluate security. We know we will never have the complete set of all possible attack vectors as new flaws are being continuously discovered. Our strategy should be to find the cause of these flaws and minimize these.

Why is security so hard? It is because security is a negative goal (MIT xPro Cyber, 2008).

A bit of explanation might help understand this better. A positive goal is where we can verify the satisfactory completion of the goal once the job is done to specification. If we were asked to prove if someone could take control of an ocean-going vessel, we could demonstrate that by someone authorized to do so and verify that we are satisfied with the result. However, if we reframed this goal to prove that, an unauthorized person could never take control of the vessel; this then is a negative goal. The burden of proof that an unauthorized person can never control the vessel as the number of possibilities increases gets more difficult. Here are some options, though not exhaustive. The unauthorized person can board the vessel with assistance from another vessel or a helicopter. Assuming they had the power to force their way through to the engine room and provided they know how to control the engine, it is a feasible possibility, however small the probability. Pirates regularly board ships. If the vessel controls are connected through cyberspace and if the external adversary knows how to take control remotely, this method of taking control is another possibility. If an adversary can spoof the GPS, they can let the authorized person on the vessel steer the vessel where the adversary likes it to go even without controlling the vessel themselves. A scary thought but is already a possibility (Humphreys, 2013; NewScientist, 2017). Every possibility for taking control of the vessel must be proven not to be feasible, an impossible task. How do we prove currently unknown possibilities? That is why security, a negative goal, is hard to prove. We sure can make it more difficult for those boarding the vessel using guards or other means, but we can never guarantee that it would never be possible. Guards can maybe prevent unauthorized people from accessing the engine room if they board the ship. However, in the GPS scenario, there is no boarding or taking control in the conventional sense, so the guards are useless in those scenarios. Hence, assuming something is never possible would be foolish, similar to the unsinkable Titanic.

We need to understand that security is a property of the system and not a specific component. If we think of the vessel as a component of the overall system, that of a vessel sailing through the oceans with cyber communications, then all the means to enter on board or access the vessel were partly external to the vessel. The GPS spoof (MAREX, 2018) is more evident as it has very little to do with the vessel but sufficient to achieve the goal of directing the vessel where the adversary needed it. GPS jammers can be bought for tens of dollars and are illegal to operate (Madden, 2018). Therefore, when we study security, we need to analyze the entire system to understand all means to improve security. For an attacker, finding the weakest link in any subsystem is all they need to penetrate the system as shown in the GPS spoofing example.

Given that security is a negative goal, how do we plan to protect assets at our nodes from malicious adversaries? Some general system level guidelines we can adopt are prevention, resilience under attack, and recovery after the attack as taught in the MIT's cybersecurity course (MIT xPro Cyber, 2008).

Prevention

We should have heard the adage "Prevention is better than cure." We can improve prevention by better designs in hardware, OS, application software layers, and networking components. Prevention makes it more difficult for the attacker to penetrate the system. If we are in a forest with a hungry lion, we do not have to outrun the lion, only outrun our accompanying colleague. Although this is a horrible thought, this is a smart security strategy. Strong passwords have the same effect on security. Most adversaries go after the weakest password users just as a lion feeds on the weakest target in the herd.

It would be better if we could team with our colleagues and "kill the lion" or at least neutralize it. One such mechanism is to share vulnerabilities across all those affected. We should go after the adversaries using this technique or at least generate prevention mechanisms to slow down or eliminate the spread of the vulnerability. Vulnerability databases are used in the industry. When companies are hacked, they want to remain silent to prevent bad publicity, but it is in our collective interest to report the incident voluntarily. We should, however, be given the option to remain anonymous to enable broader participation and adoption across the industry.

Newer technologies are coming up, and we already discussed quantum communications as a means to improve channel information leaks. These modern technologies will help improve prevention and could open up new doors to attack. However, in the meantime, some general principles to strengthen security design at the hardware and software levels are the following techniques.

Complete Mediation

Complete mediation says if we care about a property, enforce it every step of the way on every single instruction. Assume every data can be tagged with metadata. This additional information provides a mechanism at the appropriate level to manage who gets to use the data. The policy can then systematically enforce properties associated with that data type. If every access, or every request by anybody on the computer system, is checked, the system will become safer. Otherwise, if we miss even one check, then of course, the attacker could exploit it. The general thought is that application programmers are thinking at a high level, so it is best if hardware or OS implements this strategy to improve efficiency. There is a computational cost to this strategy, and so hardware is computationally the best level to implement complete mediation, but this puts a burden on flexibility for changes in design after implementation.

This principle could also be implemented flexibly at the OS level. Suppose we want to protect a resource, we have to ensure only those authorized and having permission can use this resource. First, we need to have a strict door with a guard program through which all requests to the resource can come in. The guard has to first verify and authenticate the request by checking if the message was modified during transmission and who made the request and if they have the permission to use the resource.

Additional protection is provided by storing transaction logs for forensics later on. These logs will help us prevent and recover from the attack. Some industries such as banking are mandated by law to capture and store network log data of every transaction on their network for years at a time. Companies like Bluelance's LT Auditor (Blue Lance, 2013) acquires network data across multiple OS, thereby providing a combined view of all transactions on the network.

Separate Privileges

Systems need to demarcate who has what privileges on data. For files, it could be read or write privileges. For code, it could be execution privileges. For critical data, it is best to have multiple parties agree to that request.

Another area of separation of privileges is in the subsystem modules; if there's a security exploit in one module, it will not affect other modules. To implement this at the OS level, we need a trusted computing base (TCB), a small piece of software that has to work correctly to enable better security. By building this smaller critical TCB with more rigor, security can be enhanced. A typical OS has 20–40 million lines of code and is so complicated that guaranteeing it to be bug-free is impossible. Because writing bug-free code is impossible and as a rule of thumb every 1,000 lines of code has a bug, it is best to keep logical modules separate when possible. TCB is a means to separate the critical, essential portion of the code from the not so critical.

Virtual machines running on the same physical hardware or different machines separating logical blocks of code are other mechanisms of separation that help prevent a complete meltdown. Or else, if there is a bug in one block of code, then at some point, it could propagate to the neighboring code base. Even though there is a performance price to be paid for code separation, it might be well worth the effort to ensure security. Separation is also not a guaranteed fool-proof methodology, as separate modules have to talk to one another to be useful. As we said earlier, we want to make it harder for the malicious adversary to take advantage. The higher and stronger the fence, the more secure we could be.

The Principle of Least Privilege

Every user should be given no more than what is required of them to do their job. A network administrator might have supreme powers over their network. Other employees are grouped into accounting, operations, maintenance, research, sales, and marketing and are given the least privilege to do their jobs and access the files that they need to, no more, no less. This principle prevents somebody from marketing going and messing up with files in accounting, which they should not, under normal circumstances. If marketing needs accounting information to look at sales numbers for an ad campaign, then they should put in a request and get access to just those numbers and not the entire accounting file system. Marketing, in this case, has request privilege but not file folder access privilege in accounting.

Classified information is handled similarly with a *need to know*. There are different tier levels for what we need to know. This compartmentalized separation of information and giving access to only those who need to know maintaining the principle of least privilege is how nations ensure that secrets are kept safe. This is a general principle of security, scalable across domains, an example of knowledge replication.

As can be seen, these principles are general enough to even translate to other complex systems in the maritime domain. Not everyone on a vessel needs to access every control of the vessel. So giving people access to the minimum level of access to do their job will keep the system safer and potentially more secure. There is no guarantee, but it makes the adversary's job more difficult. If the costs of the exploits are high, then adversaries give up or go elsewhere. Separating job roles on a vessel and keeping the access to assets at a minimum needed to do the job have the same security implication. Enforcing these principles is a means of improving security by design.

Cyber is a virtual layer overlaid on top of the physical system and influenced by our social layer. Human social behavior has to be managed if we need to keep cyberspace safe. Hence, managing personnel privileges should also be part of the overall security strategy.

Resilience Under Attack

If we can trust only a small portion of the code, the TCB, how do we carry out bug-free computations without trusting the remaining code? The untrusted code can be made to operate on encrypted data with higher security benefit but at a higher computational expense. *Fully homomorphic encryption* technology can carry out arbitrary computation on encrypted data. In short, we could keep all the data encrypted and compute on this data set without having to see the actual data. The output of the data will also be encrypted, and only the owner of the data can decode the encryption. This technology is still maturing, but when ready this technology will be a case of resilience under attack. This technology would usher in the next generation of cloud computing.

Another method to provide resilience is to use redundancy in subsystems. Redundant systems on ships are a good analog to understand this concept. Redundant ship systems were designed to prevent catastrophic operational failures at sea. However, this idea of redundancy translates well to strengthen cyber systems. The goal is to provide guaranteed operation despite failures. Once the attack is detected, we can isolate the corrupted system and then switch to the redundant backup to continue. As with all systems, there is a cost penalty for supporting redundant systems. Hence, we need to determine which subsystems need to be duplicated judiciously.

Recovery After Attack

So far, we have been discussing proactive security measures. Here we will discuss reactive security measures. The general strategy here is one of (1) Detect, (2) Isolate, and (3) Recover. Standard antivirus software uses this strategy. For known virus signatures, antivirus software will prevent the known viruses from infecting the system. However, if a new virus is discovered, then the signature database has to be updated, and if the new virus has already affected the system, then the antivirus software has to restore files back to the last checkpoint. Restoring is a tricky process, as not only corrupted files will be restored back to a safe checkpoint state but proper uncorrupted files during that period also will. Hence, useful work done by some users is lost. Newer technologies currently have more exceptional trace data resolution by creating action history graphs. These graphs can then be used to recover quickly and with minimal disruption. Action history graphs are a field of active research.

The general theme that arises is one of flow tracking the data as it is altered over time. The strategy seems to be to monitor the metadata and use those changes to manage any adverse behavior. The metadata could contain type, extent, and ownership of data as the standard parameters monitored. The analysis of metadata signature behavior could also offer potential input to anomaly detection software for zero-day unknown attack detection.

Future Trends

In this section, we discuss some of the latest technologies and issues that will affect cyberspace and its security.

Quantum Computation, Communication, and Encryption

Quantum computers work on particles that are in superposition, thereby enabling parallel computations of a multitude of states simultaneously. If we can physically realize such a machine at scale, then modern-day encryption will be cracked, and we will then have to resort to other means such as quantum cryptography. However, there are arguments against quantum computers being able to scale (Moskvitch, 2018). Only time will tell. Quantum entanglement occurs when a pair of particles interacts physically, even though separated by a distance. A laser beam fired through a certain type of crystals can cause individual photons to be split into pairs of entangled photons. Einstein's famous "spooky action at a distance" property of entangled quantum particles can be separated by large distances of the order of hundreds of miles or even more. Recently, the Chinese have demonstrated the transfer of information across 1,200 km, thereby providing the technology for ultrasecure communication networks and, eventually, a space-based quantum Internet (Popkin, 2017).

Multiparty Computation

Fully homomorphic encryption is a technology that can carry out arbitrary computation on encrypted data. Let us say we want to calculate the average pay in the shipping industry to compare it to the offshore sector without any individual revealing their paycheck amount. Using homomorphic encryption, we can compute the average salary on everyone's encrypted income data without knowing the individual's salary values, if the majority do not collude. Encryption ensures that if there is a bug in the untrusted code used to compute the average value, it will not expose the underlying private income data. This technology when mature will prevent many of the data breaches that have been in the news lately. All data will be encrypted and hence remain anonymous. Unfortunately, fully homomorphic encryption has a computational load that is close to multiple orders of magnitude compared to computing on unencrypted data, and this technology is not yet ready for prime time. When available, this technology will be a case of resilience under attack.

AI and Machine Learning

There is much hype about companies using AI to help with cybersecurity, but most of the technology out there is training large sets of data using machine learning (ML) (Newman, 2018). The most common techniques in ML are classification where labeled data, for example, spam or not spam, is used to train a classifier to send spam email to the spam folder automatically. Spammers are getting smarter and have the same ML tools at their disposal. This same classifier technology can be used to classify virus or, in general, malware signatures.

Currently, there have been advances in AI and ML where zero-day attacks, attacks never seen before, can be detected. These generally use the technique of anomaly detection of changes in typical patterns of behaviors to look for potential attack vectors. Behavior analysis is similar to the credit card company's flagging a purchase when there is abnormal purchase at locations the user is not expected to be at or in type and quantities that the user does not regularly purchase.

Another technique is anomaly detection, which uses baseline operations to flag unusual behavior. Behavioral analytics is a new cop in town. Earlier this year, Palo Alto Networks introduced Magnifier, a behavioral analytics solution (Oltsik, 2018).

Generally, a man-machine symbiosis approach works best where ML algorithms flag unusual behavior and the human in the loop can verify if new behaviors need to be blocked.

The major impediment to these technologies scaling is privacy and sharing of data across companies. Once we can get around these issues, then defensive techniques will not be so fragmented and will have higher success.

Blockchain

A blockchain is a decentralized, distributed, public digital ledger used to record transactions so that the list of records, called blocks, cannot be altered retroactively without alteration of all subsequent blocks. The blocks are linked and secured using cryptography.

Blockchain technologies were developed through breakthroughs in cryptography and security. It offers a secure approach to storing information, making transactions, and establishing trust with mutually unknown actors. Here are some examples that use blockchain to enhance cyberspace security. Guardtime used blockchains to create a keyless signature infrastructure and secured all of Estonia's 1 million health records with its technology (Guardtime, 2007). REMME's blockchain can authenticate users and devices without the need for a password (REMME, 2016). Obsidian Messenger (2017) is a blockchain-based messaging platform (Barzilay, 2017).

Ethics

Cyberethics is the philosophic study of ethics about computers and the users who use them. The critical goal is to study how user behavior on computer networks affects individuals and society. The 10 commandments of computer ethics state that one shall not interfere, harm, steal, and snoop on others' property (Barquin, 1992). It also says that we should think about the social consequences of the systems we are designing. A discussion on ethics leads us to cyber warfare and autonomous weapons driven by AI. We should have open debates about these topics as a society and put policies in place to ensure we do not self-destruct. Unlike mutual nuclear deterrence using the principle of mutually assured destruction, cyber warfare is a little fuzzy given that nonstate actors can have access to this technology, and without a geographic boundary to contain the adversary, it becomes challenging to defend against these threats.

Conclusion

We have shown that cyberspace is a reflection of human networks and has the advantages and flaws inherent in these human networks. If we improve trust in the system, we can improve security. Just as fake news wreaks havoc on democracy by confusing the average informed voter, lack of trust makes cyberspace less reliable to depend on. The full potential of this human engineered network will never be met if trust on this network is not improved. Although this viewpoint is simplistic and not an exact model, we believe it helps simplify the complexity of cyberspace and the wide variety of attacks that are possible. We hope that the average person can see the big picture and can make the entire system more robust by intelligently participating in this endeavor. For the specialist, we need to drill down further to help develop specific solutions. As an example, McGillivary (2018) discusses why maritime cybersecurity is an ocean policy priority and how it can be addressed.

The analogy we provide is similar to doctors and patients combining to improve the health of our population. As patients on the network, we need to take care of our health to the best extent possible, and the doctors will intervene when it is beyond our capability. If the average person is better informed, the health of the population will improve. We hope this article has given a simplistic but useful look at the domain of cyberspace enabling better security and hence resiliency of the whole cyber ecosystem.

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PAPER

Why Maritime Cybersecurity Is an Ocean Policy Priority and How It Can Be Addressed

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ABSTRACT

Maritime cybersecurity is developing as an issue that affects the ocean. Recent security breaches cost shipping companies hundreds of millions of dollars and put marine ecosystems at risk by disabling ship controls and increasing risks of collisions and hazmat spills. Additionally, most new ships are designed to transmit engine performance data ashore to allow timely maintenance and efficient operation. However, many ships still prohibit such data transmission due to security concerns, resulting in increased ship emissions and environmental risks from accidental release of oil, hydraulic fluids, or lubricants. Similarly, research vessel data are routinely sent ashore, but security concerns for their computers are also increasing, especially when they operate in global ports and oceans. Maritime cybersecurity is also critical as autonomous ships are being developed. Addressing maritime cybersecurity is therefore a valid area of scientific policy research and important for ocean science operations.

The International Maritime Organization (IMO) has called for improved maritime cybersecurity, and the U.S. Coast Guard also recently released a Navigation and Vessel Inspection Circular (NVIC; NVIC 05-17) on maritime cybersecurity for comments. The newly established Maritime Cyber Security Committee of the Marine Technology Society is coordinating maritime cybersecurity best practice information, contacts for cybersecurity professionals, and lessons learned on responding to cyberattacks to make this information broadly available. We review here various stakeholder approaches to maritime cybersecurity, outline available resources, and discuss how advanced methods, including optical communications and quantum encryption, will improve maritime cybersecurity. Scientists have a role in developing and implementing maritime cybersecurity methods and policies to ensure safe ship operations and improved environmental security for the oceans.

Keywords: shipping, cybersecurity, port security, quantum encryption

> *"The old need cannot see the coming need."*
> *Time Is a Ship That Never Casts Anchor: Sami Proverbs*—Harald Gaski, 2010

Background and Introduction: The Scope of the Problem

Shipping has continued to increase in importance in global trade, complete with subsidies from various countries to increase their proportion of this lucrative market (cf. Anonymous, 2014). In an era when the Internet-of-things is beginning to extend to ships, this puts ship and shippers' computer systems at an increasing risk (Quaintance, 2017). Ships that were built to continuously transmit data on engine and ship systems' status ashore to enable just-in-time diagnostics and repairs in some cases have had these systems intentionally disabled due to security concerns with the transmission of such data. The recent hack of Maersk shipping lines in June 2017, which caused the shutdown of Maersk operations in 13 international ports and losses of $300M, was a wake-up call to many about the seriousness of maritime cybersecurity risks (Baraniuk, 2017). However, there have been numerous other cases of shipping hacks, with reportedly over 300 unclassified reports of such hacks to date. In some cases, cybersecurity breaches involved compromising the information for containers aboard or offloaded from ships so that they could be stolen (Baraniuk, 2017; Hayes, 2016). Some hacks have shut down bridge operations with ransomware demands, or ship navigation Electronic Chart Display and Information Systems (ECDIS) system security flaws were targeted (Luciano, 2017). At minimum, these put ships out of operation for some period of time, and shipping companies suffer financial losses from inability to sustain normal operations. In other cases, such as the Clarkson shipping hack (Anonymous, 2017g), where the hack allowed manipulation of ship manifest lists with potential smuggling of containers, these hacks have potentially further damaged the company's reputation by possibly putting client information at risk as well (Wingrove, 2017). The maritime cybersecurity hacks are not limited to commercial shipping or hacker activity alone; they have also been undertaken by governments such as North Korea and Russia and deployed against commercial and military vessels, mostly by hacking or spoofing GPS, Automatic [ship] Identification System (AIS), or ECDIS systems (Dunn, 2017; Vaas, 2017). The risk from positional spoofing was judged so probable, that as of 2015, the U.S. Naval Academy began again requiring its personnel to undergo training in celestial navigation for the first time in a decade (Vaas, 2017; Zorabedian, 2015).

The military aspect of maritime cybersecurity is not at all lost in the area of national defense, for which warnings have been coming for some time (cf. Hayes, 2016; Lyngaas, 2015). Federal agencies responsible for the safety of shipping, including particularly the U.S. Coast Guard, have been interested in how best to approach the problem of providing standards and guidance for cybersecurity compliance for shipping (cf. Heckman et al., 2017). It is clear from cyber penetration tests that the majority of marine shipping vessels are vulnerable to cyberattacks (Naval Dome, 2017b). The question facing industries using ships, as well as ports and federal and international agencies, is how best to address this issue.

Approaches to Cybersecurity From Industry, Federal, and International Agencies

There are questions as to whether it is best to look at the means used to address maritime cybersecurity issues from a "top-down" approach, that is, from international and federal agency plans/mandates, or a "bottom-up" approach, that is, the one used by the industry, which often moves more rapidly than governments to address security issues. The shipping industry, which can suffer financial losses from cybersecurity attacks, has long been working to improve vessel tracking and position reporting using real-time AIS methods, which at least theoretically (if not hacked) let them know where their assets are located (Schill, 2017). Shipping companies and satellite communications companies used by the shipping industry have turned their attention to cybersecurity issues, releasing their own recommendations (cf. DNV GL AS, 2016) and calling for the international development and enforcement of cybersecurity standards for data management via the International Maritime Organization (IMO) and American Bureau of Shipping (ABS) (Anonymous, 2016, 2017d). The oil and gas industry has an Oil Companies International Marine Forum (OCIMF) that administers a Ship Inspection Report Program (SIRE), which in 2018 added a cybersecurity requirement for all vessels subject to those inspections (Anonymous, 2018a). These actions by industry have been reflected in the prominence of this issue in a number of industry shipping conferences (U.K. Port & Harbor Conference [Parsons, 2016]; GST Shipping 2030 Conference; Maritime Risk Symposium, 2017 [Gianfalla, 2017; Hudson, 2017]; and Port Security Technology Conference, 2017). Cybersecurity is also a general issue of interest for the Japanese Port and Airport Research Institute (PARI, 2017) and specific ports such as the Port of Long Beach (Parsons, 2016) and Port of Los Angeles, the highest shipping value port in the United States (>$140B in 2014; Noll, 2017), which has established a centralized Cyber Lab to combat a torrent of cyber-hacking attacks daily (Anonymous, 2017f). In 2016, the IMO released "Interim Guidelines on Maritime Cyber Risk Management," which were finalized in 2017 (IMO, 2016, 2017) and are to be implemented on ships by 2021. Additionally, in late 2017, the IMO launched a network of five global centers of excellence in marine technology, called Maritime Technology Cooperation Centers (MTCCs), which should improve the adoption of these cybersecurity standards internationally (Anonymous, 2017h). A compilation of industry maritime cybersecurity guidance from diverse sources may be found at http://becyberawareatsea.com/guidance; one component of which is shown in Figure 1.

These industry initiatives have been supplemented within the United Kingdom by the release of guidance documents from the U.K. National Cyber Security Centre (2018) and a U.K. Vessel Code of Practice for shipping, from their Department of Transport (Boyes & Isbell, 2017). Within the European Union (EU), the first maritime cybersecurity assessment was done in 2011, and subsequent general security reports have also been promulgated, which call for training and cooperation but are not focused on cybersecurity (European Agency for Network and Information Security [ENISA], 2011; EU, 2014). Beginning in May 2018, the EU adds two new pieces of cybersecurity legislation that will have broad effects: the EU General Data Protection Regulation (GDPR), for which stiff

FIGURE 1

Cybersecurity approach from *The Guidelines on Cyber Security Onboard Ships*, 2017 (https://www.bimco.org/products/publications/free/cyber-secuirty).

penalties for noncompliance can be levied against companies doing business in the EU, and the Network Information Security (NIS) Directive, which is left up to individual member countries to enforce (Anonymous, 2018a).

Within the United States, the issue of maritime cybersecurity falls among several federal agencies. There is an obvious defense component to cybersecurity. In 2017, the U.S. Cyber Command was split from the National Security Agency, and independent commands were established within the Army and Navy, both of which are now operational (Baldor, 2017; Obsorn, 2017). Understandably, ship cybersecurity for national defense lies principally with the Navy as one component of an overall Navy defense strategy for the future (Richardson, 2016). Within the realm of federal guidance on cybersecurity, the National Research Council (NRC) and the National Academies of Science, Engineering, and Medicine (NAS) have produced a series of reports dealing with cybersecurity, including a review of existing cyberchallenges, how the country can improve its cybersecurity, how it can better deter cyberattacks, what is required in terms of international policy initiatives, how transportation infrastructure can be protected, and how public policies interface with executing cybersecurity initiatives (NAS, 2007, 2010, 2015, 2016, 2017a, 2017b, 2017c; NRC, 2014). Partially, as a result of these reports, the Office of the President issued an Executive Order (EO) in May 2017 on cybersecurity for federal networks and critical infrastructure, which has since been a subject of discussion in attempts to clarify the specifics and practicalities of the path forward (Anonymous, 2017e; Lohrmann, 2017; Trump, 2017).

Additionally, in the areas of cybersecurity research, the National Science Foundation (NSF) has established a Cybersecurity Center of Excellence and Center for Trusted Scientific Cyberinfrastructure (NSF, 2016, 2017). Likewise, for more applied cybersecurity technologies, the Defense Advanced Research Agency (DARPA) has tapped Rockwell Collins to assist in protecting computers, including those on unmanned systems, from cyberintrusions through its partnership in the DARPA High-Assurance Military Systems (HACMS) program (Anonymous, 2017b). DARPA has also more recently initiated solicitations for the Harnessing Autonomy for Countering Cyberadversary Systems (HACCS) program for land, sea, and satellite assets (DARPA, 2017; Lane et al., 2017) and also for the Configurational Security (ConSec) program, which is aimed at automating computer systems configuration management to minimize risks of cyberattacks (Keller, 2017b).

Within the Department of Transportation, the U.S. Maritime Administration (MARAD) has also issued guidance about the cybersecurity of essential transportation systems, including certification of commercial carrier and passenger vessels (MARAD, 2017). General guidance on cybersecurity methods are provided by the U.S. National Institute of Standards and Technology (NIST) as directed by the 2013 Presidential EO 13686, Improving Critical Infrastructure, Cybersecurity, as well as the Cybersecurity Enhancement Act of 2014 (Public Law 113-294). In response to these directives, NIST developed and released a Cybersecurity Framework Version 1.0 in 2013 and a Version 1.1 on April 16, 2018. The key components of the V.1.0 Framework were to provide guidance on identifying cybersecurity needs for organizations, methods to accomplish those cybersecurity needs in terms of cyber protection, detection of cybersecurity breaches, planning for responses to such breaches, and recovery from breaches (see http://www.nisto.gov).

Additionally, NIST has also focused on the National Initiative for Cybersecurity Education (NICE), part of which is the establishment of a Cybersecurity Workforce Framework that recognizes that training personnel is also a key component of enabling cybersecurity (NIST, 2018a, 2018b) (see Figure 2).

For maritime cybersecurity, the Department of Homeland Security (DHS) deals with the security of critical infrastructure (cf. http://www.dhs.gov/stakeholder-engagement-and-cyber-infrastructure-resilience), including ports and harbors. Furthermore, as a component of DHS, the U.S. Coast Guard deals specifically with the safety and security of shipping as well as ports. A recent issue of the "Coast Guard Proceedings" was dedicated to maritime cybersecurity and featured a series of articles on various aspects of this topic (cf. Goldstein & Kneidinger, 2014/2015; http://uscgproceedings.epubxp.com/i/436751-win-2015/47). However, the U.S. Coast Guard is not itself an agency with a specific expertise in cybersecurity technologies, and it cannot impose its own suggestions or requirements about cybersecurity practices on other countries or international companies. Instead, the Coast Guard has sought to engage with the broader maritime community to work synergistically toward improved cybersecurity, establish cybersecurity best practices, and promote compliance with these recommendations. In July 2017, the Coast Guard released a Navigation and Vessel Inspection Circular (NVIC) Number 05-17, called "Guidelines for Addressing Cyber Risks at Maritime Transportation Security Act (MTSA) Facilities" (Federal Register, 2017, and/or Manning, 2017). This document referred to the Coast Guard Cyber Strategy document (U.S. Coast Guard, 2015) and called for public comments on how best to address the issues of maritime cybersecurity in relation to its proposed policies and procedures intended to mitigate cybersecurity risks. These procedures call for ship owners and operators to conduct cyber risk profile assessments as part of their facility security plans. The NVIC also lays out best practices for cybersecurity derived from NIST guidelines, including guidelines on personnel responsibilities relating to cybersecurity. The request for comments also included a solicitation for comments relating to how the guidance provided by the Coast Guard would need to be updated in the face of newly developing technologies.

FIGURE 2

The NIST NICE has established a Cybersecurity Workforce Framework that is intended to ensure a cyber-workforce is developed that can monitor and administer cybersecurity standards correctly (NIST, 2018a, 2018b).

Cyberattack Reporting Requirements or Who Ya Gonna Call?

There have been many discussions about preventing cyberattacks, but there also needs to be a broader dissemination of what protocols need to be followed when there is a cybersecurity breach; most ship crews and management agencies do not know what to do if they are hacked. From the shipping company viewpoint, this is not only a cybersecurity issue; there can also be serious financial costs if shipping operations are shut down. So what are the protocols for responding to a cyber-breach? Heckman et al. (2017) provide a fairly comprehensive list of U.S. Coast Guard and industry approaches to this issue. Coast Guard guidance on "Reporting

Suspicious Activity and Breaches of Security" (December 2016) notes that information reported to the Coast Guard is "not subject to routine public disclosure," so that the Coast Guard wants to be informed of security breaches, but they will not disclose such information publicly, in ways that might affect the business of any company whose security has been breached. This same guidance calls for maritime security breaches to be reported to the National Response Center (NRC; 1-800-424-8802), as well as noting that reports can and should also be made to respective Captains of the Port(s) and also the National Cybersecurity and Communications Integration Center (NCCIC; 1-888-282-0870), which is a 24/7 cyber situational awareness center that links federal and intelligence agencies with law enforcement agencies. Reports to the latter should specifically include mention to the NCCIC that the reporting component is a Coast Guard–regulated entity, so that their data will be forwarded appropriately to the NRC and Coast Guard (and also the FBI). The EU (Europol) also has a URL for reporting cyber-incidents, https://www.europol.europa.eu/report-a-crime/report-cybercrime-online, with reporting criteria that vary by country.

So these are the reporting requirements from the Coast Guard and/or Europol, but how does this assist in responding with a cybersecurity breach? There will be some assistance forthcoming from the agencies reported above automatically, but those that have been breached can also specifically request assistance from the Industrial Control Systems Cyber Emergency Response Team (ICS-CERT) (https://ics-cert.us-cert.gov/), which, like the other federal agencies involved, has published their own "Recommended Practices" advice (cf. https://ics-cert.us-cert.gov/Introduction-Recommended-Practices). As noted above, the NCCIC and NRC reporting mandated by the Coast Guard also goes to the FBI. The FBI's "InfraGuard" program and its webpage "iGuardian" (cf. https://www.fbi.gov/resources/law-enforcement/iguardian) are a joint effort with the business community established in 2013 specifically to protect critical national infrastructure by providing a cyber-breach reporting mechanism and activating triage response to industry for cybersecurity breaches.

If a shipping company or port suspects that they may have been breached and wants to see what other activity in a similar vein may have taken place, they can access the National Suspicious Activity Reporting (SAR) Initiative webpage (https://nsi.ncirc.gov/). Note that this webpage is not for reporting incidents but contains a log of reported incidents jointly maintained by DHS, the FBI, and local law enforcement agencies. Additionally, the Coast Guard recommends that vessel and facility operators participate in their local Area Maritime Security Committees (AMSCs) (http://www.dco.uscg.mil/Portals/9/CG-FAC/Documents/AMSC%20Consolidated%20reports/2016/AMSC%202016%20Annual%20Report%20(signed).pdf?ver=2017-11-08-084656-947), contact information from which can be obtained from the nearest Captains of the Ports or by contacting the Coast Guard Office of Port and Facility Compliance (202-372-1132).

The Question of Methods

Certain cybersecurity approaches are focused on securing internal computer systems and preventing hacking into those systems (cf. PAS Global, 2017). Version 1.1 of the NIST Cybersecurity Framework included a more detailed consideration of validating the identity of online entities to enable more secure management of supply chain cybersecurity, which included expanded focus on the NIST Trusted Identities Group (TIG). The TIG began in 2015 as a series of pilot programs where the government would certify the identity of commercial partners through an Identity Ecosystem Framework (IDEF) established through private sector partnerships that established an IDEF Registry, which provided authentication credentials for companies at three assurance levels that they were who they said they were. Among other things, such assurance in Version 1.1 was updated to remove the option of one-time passwords via email and limit them to SMS messages (text messages to cell phones) as well as the use of security tokens, because those could be stolen. Three Authentication Assurance Levels (AALs) were established, where in AAL 1, reauthentication was required every 30 days; AAL 2, every 30 min of online use; and AAL 3, every 15 min of online use. These reauthentications could be done by self-assertion, remote identification assertion proof, or in-person proofing. One consequence of the adoption of these new requirements by some federal agency vessels in the early summer of 2018 was that the bandwidth required for such security reauthorizations overwhelmed the available ship satellite communication bandwidth and effectively shut down ship communication systems until, weeks later, additional satellite bandwidth contracts and software and reauthorization frequency adjustments could be put in place—one indication of the unexpected consequences of the attempted implementation of these new cybersecurity requirements in an industry where satellite communications bandwidth is far more limited than nonmaritime computer networks.

Other approaches have been directed at securing communications with systems outside an internal computer system, as is inherently the case between ports and ships, and ships and ship managers. Wireless communications with satellites have one interesting security communications protocol initially funded by NASA for the Interplanetary Internet that was developed by Vinton Cerf. There was a need for a new protocol for the Interplanetary Internet because communicating with distant spacecraft involved delays and disruptions for which the usual Internet protocols were insufficient. Therefore, Cerf developed delay and disruption-tolerant wireless networking (DTN) protocols, which overcame those limitations of standard Internet communication protocols. As it happened, the DTN protocol also had an advantage in providing higher bandwidth than other wireless communication protocols, while also providing high levels of communications security (cf. the Internet Engineering Research Group DTN webpage, https://irtf.org/concluded/dtnrg). Once developed, the DTN protocol has been used to provide secure communications between unmanned systems, including multiple networked autonomous underwater vehicles (AUVs), surface vessels (ships and autonomous surface vessels [ASVs]), and manned and unmanned aircraft (McGillivary et al., 2012a, 2012b). The DTN method is now being adopted for free-space optical communications by a consortium including NASA and the U.S. Naval Research Lab, and commercial satellite communications operators. For optical communications, just as for wireless communications, use of the DTN protocol will again improve performance if data transmissions are interrupted for any reason but will also help to ensure the security of optical communications. Efforts to develop underwater optical communications are also under way in earnest (cf. Baghdady et al., 2016a, 2016b) and remain a goal for naval forces (Keller, 2017a), for which DTN protocols will also be useful.

Industry has developed its own approaches for dealing with both internal and shore-to-ship communications cybersecurity, and there has been a particular emphasis on cybersecurity within the oil and gas industry. The oil and gas industry is heavily involved in shipping (cf. Goel, 2017) and has been the subject of hacks with potentially very dangerous consequences (Bensalhia, 2015; Groll, 2017; Paganini, 2015). Among the approaches suggested to improve cybersecurity is the use of modified hashing methods instead of encryption (Jackson, 2014) or methods of format-preserving encryption (FPE; Roy, 2017). However, another method that appears to be under consideration for broader implementation is the use of machine learning methods to analyze data networks in near-real time, a method commonly called Continuous Diagnostics and Mitigation (CDM) (Anonymous, 2015; Goldstein & Kneidinger, 2014/2015; Martin & Rajasekaran, 2016). CDM methods will continue to be valuable as machine learning and artificial intelligence methods are increasingly used in cybersecurity systems. However, as several National Academy reports on cybersecurity have noted, pushing software updates and continuing to improve cybersecurity methods remain problematic (NAS, 2017a, 2017b, 2017c).

Autonomous Vessels and Unmanned Shipping

A decade ago, long-range unmanned ASVs of varying sorts were being developed, from the wave-powered Wave Gliders (http://www.liquidr.com) (McGillivary & Hine, 2007; McGillivary et al., 2007); to "robo-kayaks" (Curcio et al., 2006) and unmanned sailboats, such as the more recent Saildrone (http://www.saildrone.com); to more conventionally fueled ASVs, such as the WAM-V (http://www.wam-v.com), and now more recent similar systems. The use for ASV technology initially was mostly in open-ocean settings, away from shipping and shipping routes, where they did not need rapid autonomous control systems and collision avoidance technologies. However, as command/control systems and positioning and other collision avoidance technologies developed, it was rapidly clear that ASVs could be used for port and harbor security (see Figure 3) (Thomas, 2017) and military uses (Tuttle, 2016). Following the development of operational protocols for safe navigation of ASVs (e.g., Kuwata et al., 2014) that were gradually agreed upon by various national and international organizations, it became clear that commercial development of autonomous shipping was possible, at least on a trial basis, and many argued that it might actually be safer than ships manned by humans (Anonymous, 2017a; Levander, 2017). Commercial interests aimed specifically at developing unmanned shipping

FIGURE 3

Autonomous systems, including underwater vessels, surface vessels, and unmanned aircraft, are coming into use for port and harbor security, and commercial shipping with unmanned vessels is already being developed and tested. Communications between all these systems require cybersecurity assurance.

inevitably arose from both traditional shipping companies like DNV GL, Rolls Royce, and Wallenius Wilhelmsen and newer firms like One Sea (Anonymous, 2017c). This has led to the development of recommended procedures from Lloyd's (2016) study and the establishment of ports and harbors as test-beds for unmanned shipping, including the Port of Rotterdam in Holland (Port of Rotterdam, 2018; Rademaker, 2017). A large-scale test-bed for unmanned shipping technologies was also established in Trondheim Fjord in Norway, operated jointly with the Norwegian University of Science and Technology (NTNU) through their Centre for Autonomous Marine Operations and Systems (AMOS) (NTNU, 2018a). Beyond just the complexities of spatial sensors and ship command and control software, the cybersecurity of this information has also been an integral concern for the NTNU program, which includes an important component of collaboration with the NTNU Center for Cyber and Information Security (CCIS) (NTNU, 2018b), so that commercial operations of unmanned ships are defended against cyberattacks. Cybersecurity continues to be an essential component of the development of unmanned shipping operations and one that will continue to require research as well as education of personnel to develop, monitor, and administer cybersecurity programs within the shipping industry. This means people will have to be educated in maritime cybersecurity, for both manned and unmanned shipping operations, as well as in the rapidly expanding world of ASVs.

The Role of Education and Outreach in Advancing Maritime Cybersecurity

The coming need for establishing standards and training programs to produce more cybersecurity specialists for all areas of the economy is well known (Platt, 2015). Within the national framework of the U.S. approach to cybersecurity, NIST has focused on the fact that successful cyber-secure systems require people trained in their development and operation (see Figure 2) (NIST, 2018b). A number of U.S. universities and colleges have established computer security programs. However, as computer connectedness within the shipping industry increases, there also needs to be an increase in cybersecurity instruction by universities focused on maritime operations. One recent development that may assist in this regard was the Congressional passage of new Maritime Centers of Excellence, which are based around consortia of community colleges (Green, 2017). These centers will have the ability to specifically train personnel with cyber-expertise who intend to work directly in the world of operational maritime industries.

An example of one school currently training students specifically in maritime cybersecurity is the Stevens Institute Maritime Security Center (Stevens Institute, 2018), whose approach includes summer courses where students can focus on cybersecurity specifically for port and shipping operations. Stevens also has a contract for developing training materials for use throughout the industry under a contract from the ABS's Cyber Security Project. Similarly, a new program at Texas A&M University has recently been set up for training cybersecurity engineers, part of which is intended to focus on maritime cybersecurity (Texas A&M University, 2018).

There remains the question of whether and how universities can best assist with developing cybersecurity solutions (Eidam, 2017), but the National Science Foundation established a Center for Trustworthy Scientific Infrastructure in 2016, as well as Cybersecurity Centers of Excellence (NSF, 2016, 2017), to assist with this effort. Moreover, NSF also listed quantum technologies as one of their top 10 focus areas for the future (Cordova, 2017). As there have been rapid technology advances in this area, it is not just possible, but also likely, that there will be an intersection between improved security and quantum technologies in the near future.

Quantum Components of Cybersecurity in the Future

Currently, encryption methods used are not based on quantum encryption methods but are susceptible to decryption using quantum computing methods. As quantum encryption methods are developed and deployed, as an interim step, there are methods being proposed that will make existing encryption methods less susceptible or hopefully resistant to hacking using quantum methods (Mandelbaum, 2018). Various algorithms have been developed, and some of them have proven susceptible to quantum hacking. One new method, termed a "modified knapsack" approach (Hamlin, 2017), has been developed and is now being tested to see if it can stand up to quantum hacks.

The use of quantum computing was until recently considered a fairly abstract and remote possibility, requiring highly specialized equipment and training. There are a few large D-Wave quantum computers in the United States with a 512-qbit capacity (Thompson, 2014), but it has not been easy for most graduate students or researchers to either learn to code for them or have the kind of access that would develop expertise in their use. However, the international push toward quantum computing has changed this picture more rapidly than many people realize. Currently, the United States still holds the international lead in quantum technologies patents, dominated by patents from IBM, but China and other countries have very rapidly increased their output of patents in this area (Brachmann, 2017). IBM has now made access to their 5-qbit quantum computer, called Q, freely accessible over the Internet (IBM, 2018). They also continue to manufacture chips with higher numbers of qbits, which are being made available to advanced researchers. In addition to now having access to quantum computers, the recent development of quantum programming languages, such as Quil, and instructional manuals on how to use them (Smith et al., 2017) will broaden the base of users familiar with quantum computing technologies. There is now even a free online 1-qbit computer available to test software instructions before running the code on a larger quantum system (Geils, 2017). Nor is IBM alone in developing quantum computing technologies; naturally, Microsoft has entered the field as well, using a somewhat different approach (Bright, 2017), as have Intel, Google, and others (Corneliussen, 2018). However, what many think may really broaden the availability of quantum computing was the development of new methods of building quantum computer chips that do not require them to be supercooled and can take advantage of chip manufacturing technologies similar to those already in use by the industry (Wagstaff, 2017). One can expect that development of this technology will be the subject of intense focus, with potential for major changes in computing methods in the near future.

Apart from simply using quantum computers as a means of increasing the capability and security of computing systems, quantum methods can also be used to change the way communications are done in the first place. Technologies have been successfully developed that allow entangled photons to be generated on even small communication satellites (cf. Tang et al., 2016). Using these technologies, China has installed fiber optic cables with quantum encryption between several of their major cities and also demonstrated free-space quantum communications via satellite that have been found to be unhackable (Courtland, 2016; Nordrum, 2017; Spender, 2017). While the U.S. Navy has continued to push for new methods of optical communications between aircraft and submarines (Keller, 2017a), it may soon be the case that quantum communications provide a viable alternative with improved security as well (Anonymous, 2018b; Gerginov et al., 2017). While there is an existing body of literature outlining methods for quantum (and "postquantum") cryptography (cf. Bernstein et al., 2009), some have continued to question the practicality of quantum cryptography (Jackson, 2013). However, with the Chinese demonstrations, now the question is not whether quantum cryptography is a good idea but, instead, how it should best be developed not just for connected computers but also to network manned and unmanned systems in the real world (Sasaki, 2017). The inevitability of this approach is reflected in a draft message to the President by the National Security Telecommunications Advisory Committee (NSTAC) in 2017, which noted that "the government should consider the impact of quantum computing not just on military or intelligence agencies, but also on critical commercial functions…and develop a plan for implementing quantum-resistant encryption schemes" (NSTAC, 2017). The benefits of unhackable quantum cryptography are obvious (cf. Herman, 2017).

Summary and Conclusions

With the integration of new navigation systems onto 1,800 Coast Guard vessels (Keller, 2014), naval vessels, and an ever-increasing number of commercial ships, there will soon be more than 200,000 vessels now believed at cyber-risk (Naval Dome, 2017a). Therefore, improvements in maritime security are needed. These include improved cybersecurity within shore-based and port operations, onboard ships, and among at-sea communication paths via satellites (Ingols et al., 2017). For federal maritime agencies in the United States, maintaining currency on cybersecurity best practices can be improved by participation in annual NIST Cybersecurity Workshops specifically for federal cybersecurity personnel. Similar NIST workshops are likewise held for industry partners. However, while method of cybersecurity protocols will continue to evolve, in general, cybersecurity methods used will be similar to those in the past and will require continuous software patch upgrades and analytics as cyber-systems move toward implementing automated real-time anomaly detection and response capabilities. However, in the not distant future, many of the problems with the inevitable unprotected cybersecurity "weak links" found in using these traditional approaches could be eliminated with a transition to quantum encryption and quantum communications. Technologically, that day may come sooner than many people think, recalling that, a decade ago, the current cell phone technology was essentially unimaginable. However, as new cybersecurity and communication methods arise, they will still require dissemination of knowledge of standards, protocols, and maritime cybersecurity expertise that will require broad awareness throughout the industry and a strong program for training maritime cyber-experts. While NIST Cybersecurity Workshops and online resource materials will help those willing and able to access them, to help improve both national and international cybersecurity in the maritime arena, the Marine Technology Society (MTS) has started a Maritime Cybersecurity and Infrastructure Committee, which has its goals of (1) providing a forum for the development and exchange of maritime cybersecurity ideas, information, and experiences; (2) advancing awareness of cyber-risk; (3) promulgating best practices to drive organizational cyber-resiliency; and (4) coordinating and disseminating standards, training documents, guidelines, and maritime cybersecurity resources through its webpage and MTS meetings. Information on the committee can be found at https://www.mtsociety.org/communities/procommittees/maritime-cybersecurity-and-infra.aspx and also at http://www.garibaldisrock.com/MCSIC/. As a reflection of community awareness of the need for increased maritime cybersecurity, the MTS Cybersecurity Committee is one source of information to assist with addressing this need.

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Advances in Distributed Fiber-Optic Sensing for Monitoring Marine Infrastructure, Measuring the Deep Ocean, and Quantifying the Risks Posed by Seafloor Hazards

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ABSTRACT

Distributed optical fiber sensors provide new opportunities for monitoring the marine environment. We review the physical foundations of this sensor technology and discuss how it can be applied to radically augment the networks of subsea sensors that help monitor fundamental marine processes and to complete our understanding of local, regional, and global interactions in this environment.

Keywords: distributed fiber-optic sensors, subsea infrastructure monitoring, seabed stability, turbidity currents, subsea seismic activity

Introduction

Distributed optical fiber sensors (DOFS) form a class of sensors that provide a continuous reading of measurands (e.g., temperature, strain) as a function of distance along the sensing fiber (Hartog, 2017). Although the technology emerged more than 30 years ago (Hartog, 1983), it continues to evolve and improve as new physical principles, optical interrogation methods, and signal processing techniques are applied to it. This class of sensor has gradually gained acceptance as a tool in industrial applications and a research tool, particularly in environmental science (Kobs et al., 2014; Striegl & Loheide, 2012; Tyler et al., 2008).

Techniques for distributed measurements of temperature, static strain, and vibration (dynamic strain) are now very well established, and recent work has allowed very fine spatial resolution (<5 cm) and extremely long lengths (>100 km) to be interrogated. Although there is a trade-off between performance parameters and the finest spatial resolution cannot usually be achieved over the longest range systems, addressing more than 1 million points on a single sensing fiber has been reported (Denisov et al., 2016).

A global push toward faster communication and efficient digital data transfer is underpinned by a growing network of more than 420 undersea optical telecommunications cables that cover a distance of over 1.1 million km (Routley, 2017). The opportunity to use spare capacity on this global network for environmental monitoring is intriguing. However, this must be tempered with a few considerations, namely, (a) the operators may have no capacity that they can make available; (b) the risk of cross-talk from sensor interrogators to communication channels through nonlinear optical effects needs to be evaluated; (c) the optical architecture may not allow two-way transmission beyond the first optical amplifier and will certainly not be possible beyond the repeater where signals are converted to the electrical domain, reformatted, and retransmitted; and (d) it should be appreciated that the undersea cable routes are designed for the efficient transmission of data, not necessarily high-priority locations for valuable environmental monitoring. For example, there is a very dense coverage across the Atlantic Ocean from New England to the United Kingdom, Ireland, France, and the Iberian Peninsula, with a few other transocean cables, for example, Latin America to Africa, as well as cables following the contours of the continents. This still leaves vast tracts of the ocean with no cable whatsoever, and this situation is far more marked in the southern oceans. New cable routes to interconnect Small Island Developing States and the proposed deployment of bespoke scientific cables provide future opportunities that could help to fill such geographic gaps in oceanic coverage (Howe et al., 2010).

The application of DOFS technology, therefore, offers opportunities for monitoring long, inaccessible assets in a cost-effective manner; however, so far, the approach has found relatively limited acceptance in a subsea context. This article provides a review of the technology, outlines some of the limitations, and discusses some of the attractive opportunities for applying DOFS in the marine environment.

Technology of Distributed Sensing

DOFS systems consist of a sensing fiber cable and an interrogation system. The sensing fiber is usually an optical fiber of the type used for long-distance telecommunications or local area networks. Therefore, sensing can be performed on unmodified fibers that were initially installed specifically for telemetry or telecommunications, on spare wavelength channels, or even on spare fibers within an existing cable. Sensing fibers sometimes deviate from such conventional designs in harsh environments. For example, fibers with special coatings or glass compositions are required to handle elevated temperatures. In the marine environment, the existing fiber cables used for telecommunications, energy interconnects, and tiebacks from offshore wind farms are usually suitable for some distributed sensing applications.

The cable structure is critical in distributed sensing. The fiber must be protected from mechanical and chemical damage and yet transfer the measurands from the external environment to the sensing fiber with minimal distortion. In the case of temperature sensing, the design of the cable is relatively straightforward in that the temperature at the fiber usually follows that on the outside faithfully and rapidly. In the case of strain measurements, the cable has the additional function of a transducer and its design affects the calibration of the sensors. The design of the cable becomes even more complex when it comes to transferring external pressure to the fiber while maintaining mechanical and chemical protection. For chemical sensing, the cabling problem is yet more challenging and has been solved in only very benign physical conditions.

The interrogation system is the set of optics, electronics, and embedded software that probes the sensing fiber and converts the returning, modulated light into a digital data stream that describes the state of the measurand(s) along the fiber.

Interactions Between Measurands and the Light Traveling in an Optical Fiber

Optical fiber communication systems are known for their ability to operate in harsh conditions, and the transmission formats and error correction codes make them insensitive, in their primary role, to environmental effects (e.g., temperature, strain electromagnetic interference). Nonetheless, a large body of research has demonstrated that, by interrogating the fiber appropriately, the effects of external conditions on many of the properties (e.g., intensity, phase, transit time, polarization) of the light that is transmitted can be exploited for sensing (Hartog, 2017).

Light scattering is central to the operation of distributed sensors, in providing the return signal and the sensitivity to the main measurands. Scattering is caused by very small-scale, naturally occurring fluctuations of the refractive index of the glass forming the fiber.

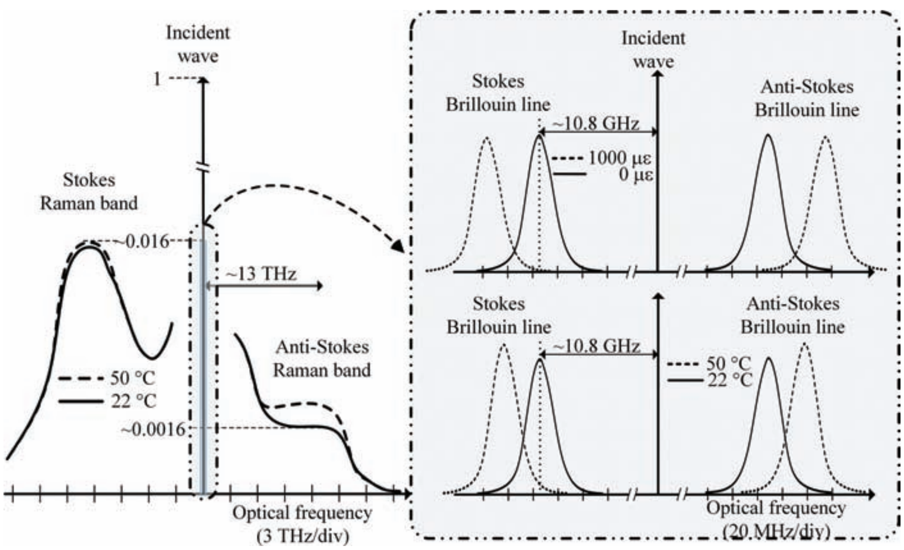
The highest proportion of the scattering (Rayleigh scattering) is caused by static inhomogeneities, which arise from fluctuations of density or composition of the glass. These inhomogeneities are thermodynamically induced during the high-temperature drawing of the fiber, when the material is still fluid and frozen in as the fiber cools. They appear on a distance scale much smaller than a wavelength of the incident light. The static nature of this type of inhomogeneity results in no exchange of energy between the glass and the incident light during the optical interaction, and so the frequency of the incident light is preserved in the process; that is, this is an *elastic* process.

Other inhomogeneities are dynamic, caused by thermally generated acoustic waves in the fiber. Very high-frequency acoustic vibrations (at c. 13 THz in silica) occur in the molecular bonds between the atoms forming the glass; their energy quanta are known as optical phonons. Raman scattering is an interaction between the incident light and these molecular vibrations; it results in an exchange of energy between the glass and the incident light in which the scattered photon loses energy equal to one phonon (Stokes Raman scattering) or gains that amount of energy (anti-Stokes Raman scattering), and so this process is *inelastic*. The anti-Stokes process requires energy to be transferred from the glass to the scattered light, and so it is strongly dependent on the temperature of the fiber at the point where the scattering occurs; in contrast, the temperature sensitivity of the Raman Stokes process is far lower (see Figure 1).

Brillouin scattering is another type of optical interaction with thermal

FIGURE 1

Schematic illustration of the spectra of the backscattered light in typical optical fiber for 1,550-nm (192.4 THz) illumination and their sensitivity to temperature. (Left) Broad frequency range encompassing all the spectral bands of interest. (Right) Expanded view showing the relationship between the Brillouin backscatter and the Rayleigh backscatter that returns at the same wavelength as the incident light. Lower right diagram applies to zero strain for two different values of temperature, and the diagram above it applies to 22°C for zero and 0.1% strain. Adapted from Hartog (2017).



acoustic waves that is also inelastic. In this case, the frequency of the acoustic waves is much lower (c. 11 GHz for an incident wavelength of 1,550 nm) than for Raman scattering, and the relevant phonons are known as acoustic phonons. Brillouin scattering occurs between the incident light and those acoustic waves that have the same acoustic wavelength as the optical wavelength of the incident light. Again, the scattered light can be upshifted in frequency (anti-Stokes scattering) or downshifted (Stokes) in the interaction. As shown in Figure 1, the intensity of the Brillouin spectra lines, as well as their frequency shift from the incident light, depends on temperature (lower right-hand diagram) and strain (upper right-hand diagram).

Thus, both Raman and Brillouin scattering processes result in new features appearing in the frequency spectrum of the scattered light. The analysis of this spectrum therefore allows several distinct physical effects to be resolved independently, and this forms the basis of most DOFS. The relative wavelengths and signal strengths of the backscattered light in typical optical fibers are illustrated in Figure 1.

Distance Resolution

The entire purpose of distributed optical fiber sensing is to provide an estimate of the value of the measurand as a continuous function of distance. Fundamental to the operation of DOFS is therefore a mechanism for resolving distance along the fiber. In almost all cases, it is the two-way transit time from the interrogator to the resolved location and back that provides distance discrimination. Thus, the measurement is conducted in a reflectometric configuration, similar to radar, sonar, or ultrasonics, but operating in this case in the 1-D confines of the optical waveguide. [Note that methods that use the difference in forward propagation time between different modes in a fiber have also been explored (Gusmeroli et al., 1989) but not commercialized probably owing to the far more challenging time requirements (three to four orders of magnitude) and their resulting inferior performance. There are, however, some examples of their use in the context of this article, for example, Dai et al. (2008)].

In most distributed sensors, the distance resolution is achieved through time-domain reflectometry: a probe pulse is launched into the fiber, and the optical signal that is returned to the interrogator is light that has been scattered, recaptured by the waveguide in the return direction, and guided back to the launching end.

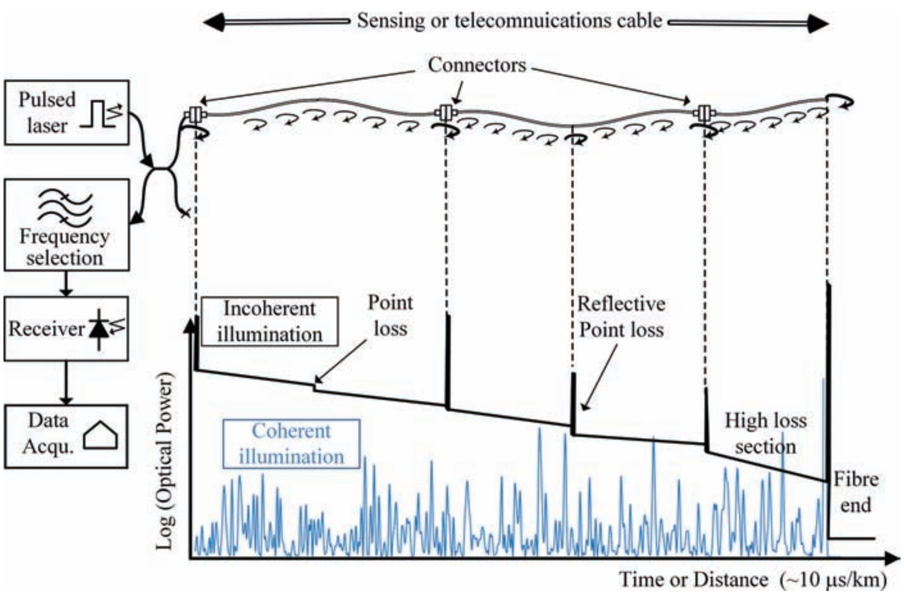
Optical time-domain reflectometry (OTDR) is a technique carried over from telecommunication practices (Barnoski & Jensen, 1976), where it is commonly used for checking the installation of new fiber cables and monitoring the state of installed links. It has been adapted for sensing by studying the signals returned from the fiber, and particularly their optical spectra, in far more detail than is required for the purposes of verifying the performance of optical communication circuits.

Distance z along the fiber is encoded into time t on the returning signal through the relation $z(t) = c \cdot t / (2N_g)$, where c is the speed of light in vacuum and N_g is the group refractive index for the sensing fiber at the operating wavelength. At 1,550 nm, N_g is typically 1.468 in a single-mode fiber, and this results in a delay of about 10 ns in the two-way transit time for each metre of sensing fiber.

The essential functional blocks in an OTDR (Figure 2) are a pulsed

FIGURE 2

Schematic diagram of an optical time-domain reflectometer and typical signals measured as a function of distance along the fiber. Black curve: with an incoherent source; blue curve: with a coherent source. Adapted from Hartog (2017).



laser source, a device for separating forward- and backward-traveling light, a receiver to convert the backscatter signal into an electrical voltage, and a data acquisition unit. In telecommunication applications, the source has low coherence (typically a relative bandwidth of 1–2%, i.e., 10–30 nm), and the signal takes the appearance of the black sloping line in Figure 2, which includes spikes caused by reflections and drops in signal power at localized loss points; its slope is indicative of the attenuation of the fiber. In distributed sensors, a frequency selection function is also used to choose the spectral components that are passed to the receiver.

Although the signal returning to the interrogator is continuous, it is invariably converted to a stream of digitized values and the sampling rate of the analog-to-digital converter determines the spatial separation of adjacent samples. This is one of the limitations on the spatial resolution of the system, another being the bandwidth of the probe signal (in usual cases, the reciprocal of the pulse duration) or that of the physical process generating the particular part of the scattered light used in the measurement.

Spread-spectrum methods, such as frequency-modulated, continuous-wave encoding or pseudorandom coding, borrowed from the field of radar, are also able to provide distance resolution based on two-way transit time and have been employed in distributed sensing (Glombitza, 1998; Park et al., 2006).

The techniques described here that are based on reflectometry differ from the recent article on earthquake detection using existing telecommunications cables (Marra et al., 2018), in which the optical fiber is looped back at the remote end and the signal is returned on a second fiber. In the case of the work of Marra et al. (2018), the signal that is measured is the integral of the dynamic strain over the entire fiber propagation path. This makes for a very sensitive measurement, but one that is not location resolved, unless multiple such measurements are available over diverse paths and can be triangulated for a location of the epicenter of the quake. It should also be noted that distributed vibration sensors, when connected to fibers that are straight, are insensitive to waves arriving perpendicularly to the fiber (Dean et al., 2015; Hartog, 2017). The sensitivity that is detected arises from the wave components that are parallel to the fiber, and this applies also the work of Marra et al. (2018). Thus, signals that are detected most likely originate from the curvature of the wave fronts of the seismic signals or from deviations of the sensing cable from a perfect straight line.

Sensitivity to Measurands

Collecting the light backscattered from a probe pulse provides information on the integrity of the optical transmission line, but it is not, in itself, useful for sensing. The sensitivity of distributed sensors to specific measurands arises from a more detailed use of the spectrum of the backscattered light. As discussed in the section on "Issues of Performance: Limitations," three types of scattering (Raman, Brillouin, and Rayleigh) are commonly used in distributed sensors to extract the information of interest from the backscattered light spectrum.

Raman-based distributed temperature sensors select the anti-Stokes Raman scattering; its intensity as a function of distance along the fiber is a proxy for local temperature (Dakin, 1984). Usually, a less temperature-sensitive spectral line (Raman Stokes [Dakin, 1984] or Rayleigh [Hartog et al., 1985] wavelength) is also captured to provide a reference to compensate for propagation losses in the path to and from each sensing point. The ratio of the anti-Stokes Raman and reference signals is used to calculate the temperature distribution. The Raman ratio derives fundamentally from the thermal excitation of molecular bonds in the material, from which the fiber is made, and it is therefore an absolute measure of the temperature of the core of the fiber at the point at which the scattering occurs. In practice, further compensation for the loss distribution along the sensing fiber and in the optics within the interrogator is required (Bolognini & Hartog, 2013; Hartog, 2017). Over short distances and limited time differences, the referencing to an anti-Stokes Raman backscatter trace acquired with a known temperature profile can be used for temperature compensation of other measurements that suffer from cross-sensitivity to temperature (Belal et al., 2010).

Raman distributed sensing technology is very well established with many thousands of installations in applications, from fire detection in tunnels, through the dynamic thermal rating of energy cables, to the determination of the flow profile in hydrocarbon wells (Bolognini & Hartog, 2013; Hartog, 2017). Systems vary in sophistication from relatively low-cost units able to monitor a few kilometers of sensing fiber with a resolution of order 2 m (and a few tenths of 1 K) to more advanced systems able to resolve 1 m or better over 10 km at a resolution of order 0.01 K as well as systems optimized for the long distances (30–50 km) required for monitoring subsea energy cables and flow lines.

Brillouin scattering is a far richer process for sensing than Raman scattering. First, it is a very narrow-band process (of order 20-MHz linewidth), and this, combined with the closer spacing between the incident light and the scattered light, simplifies the loss compensation problem in long-range systems based on the intensity of the backscattered light. Second, the frequency shift (ν_B) between incident and scattered light is itself sensitive to temperature and strain, and this provides an independent measurement that allows temperature and strain to be extracted from measurements of intensity and ν_B (Belal & Newson, 2012). Subject to prior calibration and separation of strain from temperature, ν_B is a measure of absolute temperature at the point of scattering. Finally, the fact that the Brillouin scattering spectrum is very narrow allows optical amplification techniques to be used to extend the sensing range while adding only acceptable levels of noise to the signal of interest.

The most important characteristic of Brillouin scattering is that it can readily be used in a stimulated mode in which two counterpropagating waves interact if their frequency difference is exactly equal to ν_B. Stimulated Brillouin scattering is a three-wave process involving the two incident light waves and a stimulated acoustic wave. Control of the two incident waves has allowed researchers to demonstrate remarkable features such as extremely fine spatial resolution (a few millimeters) and very fast update times (of order 10 ms) (Hotate, 2013; Motil et al., 2016) and, in some cases, apply them to practical problems (Imai et al., 2010; Kumagai et al., 2013). A related technique allows single, addressable points to be interrogated on a microsecond update time scale over short ranges (Mizuno et al., 2016).

We conclude this brief description of the main distributed sensing techniques with systems that measure rapidly changing, that is, dynamic, strain. Under broadband illumination, the Rayleigh backscatter signal is simply a measure of the probe power along the fiber and how effectively scattered light is captured by the waveguide in the return direction (Figure 2, black line). However, with narrowband illumination (where the native source bandwidth is far narrower than the inverse pulse duration; i.e., the coherence time of the source is much longer than the duration of the probe pulses), the backscatter signal acquires a completely different character (blue line in the lower part of Figure 2). In this case, the light returned from each resolvable section of fiber ($\delta z = c \cdot \tau / (2N_g)$, where τ is the pulse duration) is the coherent summation of the electric fields reradiated from each of the myriad of scatterers within δz. The relative phase of each of these re-emitters is therefore critical to the amplitude and phase of the optical wave arriving at the detector. Each section δz of fiber is thus functionally equivalent to a multipath interferometer, and minute changes in the relative locations of the scatterers can radically change the returned signal. Coherent Rayleigh backscatter is thus a very sensitive indicator of strain, with modern sensors resolving extensions of order 1 nm over distances of a few meters. Changes of local temperature, which alter primarily the refractive index of the sensing fiber, are also able to modulate the backscatter signal.

In coherent Rayleigh backscatter, the phase of the backscattered light, as well as its amplitude, is modulated by the measurand. The coherent Rayleigh backscatter signal is random (determined by the random dispositions of the scattering elements within each resolvable section) but stable if the fiber condition is itself stable and the frequency of the probe source is also constant. One is therefore exploiting dynamic changes of this random signal. The transfer function from strain to amplitude is itself random and nonlinear; nonetheless, these effects are commonly used in applications such as intrusion detection where the threats can be classified despite the nature of the sensor response.

In applications where signal fidelity is important, it is usual to determine strain from the phase change differentiated over a defined fiber interval known as the gauge length, wherein the differential phase varies relatively linearly with strain (Hartog & Kader, 2012). A number of different techniques have been devised based on this approach to achieve a distributed vibration sensor. Such a sensor not only returns the spatial existence of a disturbance but also quantifies the time-varying magnitude of the strain at each location along the fiber (Hartog, 2017; Hartog & Kader, 2012; Hartog & Liokumovich, 2013; Hartog et al., 2013), an extension by 1 nm of the gauge length resulting in ~9.4 mrad of phase change.

In the differential phase measurement, the measurand information that is represented by the phase is of course restricted to the $[-\pi, \pi]$ range, and when the underlying physical parameter varies sufficiently that this interval is exceeded, the measured value simply wraps around to remain within $[-\pi, \pi]$. In order to reconstitute the true time dependence of the measurand, it is therefore necessary to unwrap the phase, a nonlinear operation that can be performed reliably (Itoh, 1982) subject to the condition that the phase varies by less than π between successive samples.

These techniques are described as "vibration" or "acoustic" sensing, but they also respond to temperature very sensitively (about 800 rad/K for a gauge length of 10 m), and the separation of the two effects usually exploits the fact that the temperature signals have a much lower frequency content compared to the acoustic signal.

The three scattering techniques, when used together, reinforce each other. For example, combining Raman and Brillouin measurements is a robust means of measuring temperature and strain independently (Alahbabi et al., 2005b; Belal et al., 2010). Similarly, the Brillouin technique provides static strain measurements at a moderate strain resolution (Belal & Newson, 2011; Maughan et al., 2001) that can be complemented by the much more sensitive dynamic strain obtained from coherent Rayleigh backscatter. Here, we use the term "static strain measurement" to denote the fact that the results can be referenced to a datum for long durations and even if the equipment is disconnected. In contrast, a dynamic measurement loses its reference to a known initial state if the equipment is turned off or disconnected. Distributed vibration sensing offers a measurement that is three orders of magnitude more sensitive (nanostrain rather than microstrain), but this measurement is dynamic only; moreover, low-frequency measurements (<1 Hz) are challenging owing to the presence of a number of noise sources with 1/f-like spectra.

A further variant of the coherent Rayleigh backscatter technique, in which the measurement is conducted over a range of source frequencies, is capabable of a static measurement, subject to an initial calibration of each resolvable section of the fiber (Froggatt & Moore, 1998; Hartog, 2017; Koyamada et al., 2009). In the case of Koyamada et al. (2009), a temperature resolution of 0.01 K at a spatial resolution of 1 m over a range of 8 km was demonstrated.

Issues of Performance: Limitations

Nonlinear optical effects set a fundamental limit on the performance of DOFS. At high optical intensities, the fiber responds nonlinearly: owing to the small size of the core (8–50 µm in diameter), moderate (1–10 W) light levels result in large optical power densities, and this brings about several undesirable effects such as stimulated Brillouin and Raman scattering. These stimulated processes build up along the length of the sensing fiber resulting in the transfer of available probe power to their corresponding Stokes lines, instead of delivering that power to the intended locations further along the fiber. This distorts any measurements based on the spontaneous versions of the processes. The refractive index itself is modified by the presence of high optical power densities (the Kerr effect) and results in broadening of the spectrum of the probe light, which degrades the measurement, catastrophically in some cases. The way in which these undesired effects limit the sensor performance depends on the physics that are used and the type of fiber. For example, the large core sizes of multimode fibers allow this fiber type to carry an order of magnitude more power than single-mode fibers, but their use complicates the design of the interrogators and the interpretation of the results (Hartog, 2017).

The noise at the receiver limits the sensitivity of the measurement, and its fundamental lower bound is shot noise, which is directly related to the number of photons that are returned by each section of fiber for each probe pulse. In most cases, the receiver itself further degrades the signal-to-noise ratio (SNR). In this context, it should be appreciated that the signal returned by distributed sensors is a small fraction of the energy launched. In the case of a sensor using 10-ns probe pulses (corresponding to δz = 1 m), the energy returned by each resolvable interval is about seven orders of magnitude below that of the forward-traveling probe pulse for Rayleigh backscatter; in the case of Brillouin and Raman scattering, the energy is further reduced by two and three orders of magnitude, respectively. The design of distributed sensors is therefore fundamentally affected by the SNR, and many schemes have been devised to overcome these limitations.

Long-distance (>10-km) sensors further compound the SNR problem with the cumulative propagation losses, and this applies to marine applications, where long sensing paths are expected. In addition to the progressive loss of signal, long sensor lengths impose a wide dynamic range on the signal that can then be difficult to digitize without loss of accuracy.

Performance: Opportunities for Enhancements

A few broad approaches have been applied to address issues of poor SNR and large dynamic range of the signal, for example, remote amplification, pulse coding, and specialty fiber design/use. The remote optical amplification (Hartog & Wait, 2009) has proven particularly effective in long-range applications such as the monitoring of terrestrial pipeline that can run for thousands of kilometers and up to ~200 km between sites where monitoring equipment can readily be installed. For sensors operating in the main telecommunication band (~1,550 nm), erbium-doped fiber amplifiers can conveniently be used both to amplify the pump and to pre-amplify the backscatter signal before it travels back to the launch end. Boosting the probe signal after it has decayed allows its power to be readjusted to the maximum allowable level (as limited by nonlinear effects), and amplifying the return signal remotely degrades the SNR far less than if the same amplification process were implemented in the interrogator, because this occurs while the signal is still relatively strong.

In one example, a system combining Brillouin reflectometry for temperature and strain measurement and coherent Rayleigh backscatter (for vibration sensing) was demonstrated over a 100-km route using discrete rare earth element–doped amplifiers sited at roughly 25-km intervals and pumped (powered) by light carried in separate fibers (Strong et al., 2008). In this case, the amplification is electrically completely passive, requiring no remotely sited electronics at all. Raman amplification, where energy is transferred from a pump wave at a somewhat shorter wavelength (1,450 nm for a sensing wavelength of 1,550 nm), has also been used to allow longer sensing lengths (Alahbabi et al., 2005a). The combination of Raman and erbium-doped fiber amplifiers has also been used to stretch the range of distributed sensors, including one example where the pump power for the initial distributed Raman amplification is also used to pump a further set of two erbium-doped fiber amplifiers, using a single fiber for sensing and conveying the optical power required for amplification (Cho et al., 2006). It should be noted that optical amplification approaches are particularly suited to sensors using Brillouin and coherent Rayleigh scattering on single-mode fibers. The optical amplification of the Raman backscatter is ineffective owing to the latter's very broad spectrum and the inevitably wide noise bandwidth that would accompany the optical gain. Similarly, the performance of optical amplifiers on typical multimode fibers (with a core diameter ≥ 50 μm) is far worse, and in practice, in-line optical amplification is not used with multimode distributed sensing systems.

Another route to enhancing the backscatter signal returned to the interrogator is pulse compression, a technique that is well known from radar (Richards et al., 2010) and other reflectometric measurements. The spatial resolution of a distributed sensor is limited by the pulse duration, so the narrower the pulse, the finer the spatial resolution. In a peak-power–limited system, a finer spatial resolution therefore implies a degraded SNR. The backscatter signal power, however, is proportional to pulse duration, and so there is a direct trade-off between spatial resolution and SNR. Pulse compression overcomes this dilemma by increasing the duration of the probe light without decreasing its bandwidth. The fine spatial resolution is encoded in the probe waveform; it is buried in the backscatter signal but can be recovered by applying a matched filter to the detected signals. A further constraint applies to long-range distributed sensors, namely, that the probe signal should not be continuous (e.g., frequency-modulated, continuous wave) because the strong backscatter from the near end of the fiber will swamp the weak backscatter from the remote end, given that these signals are present simultaneously at the receiver. The probe waveform must therefore be of limited duration, and this has led to the design of code sets [Golay complementary codes (Nazarathy et al., 1989) or simplex codes (Soto et al., 2010)] that are of finite duration and yet have the necessary correlation properties to allow a precise recovery of a signal that is equivalent to that produced by a single pulse, but stronger by a factor equal to the number of pulses in the code. The resulting improvement in the SNR is proportional to the square root of the code length.

Special fiber designs can also be used to tackle deteriorated SNR performance and/or dynamic range of the sensor. The physical processes described so far rely only on the natural state of the glass in the optical fiber. The measurements can, and usually do, use conventional fibers designed for telecommunication systems; however, specially designed fibers are used in more challenging applications. Thus, the coatings designed for the relatively benign telecommunication application are generally unsuited to high temperatures, and so specialized coatings able to operate at up to 300°C for polymer coatings and higher still for metallic coatings have been devised for these cases. In the harshest cases, a hermetic inner coating is used to retard the ingress of hydrogen and special glass formulations that are more resistant to the conversion of hydrogen into OH bonds (which render strong absorptions at some wavelengths of interest) are adopted.

In the case of Brillouin-based sensors, the cross-sensitivity between temperature and strain has led to research on fiber designs that have markedly different frequency sensitivity coefficients compared with conventional designs, to allow the cause of changes in the measured frequency to be disambiguated (Law et al., 2011; Sikali Mamdem et al., 2014).

Another strand of research in special fibers for distributed sensing concerns increasing the strength of the backscatter return for a given probe energy. Including dense, weak reflectors in the fiber achieves that objective without substantially increasing the propagation losses or lowering the threshold for nonlinear effects, because most of the energy extracted by the reflectors from the forward propagating light is coupled back into the fiber (Englich & Hartog, 2016). In contrast, the normal scattering process redirects the lost light almost uniformly in all directions. The efficiency in the reuse of the lost light increases by more than a factor of 100 in this approach, which however adds substantial cost to the sensing fiber. It will therefore most likely find applications where enhanced performance is required in a relatively limited zone, for example, to monitor a particular section of a subsea asset (perhaps a manifold running between a wellhead and a separator, electrical/communication cable or oil pipeline interacting with a rapid-flowing sediment density flow, etc.) with a higher resolution than the remainder of the infrastructure.

Opportunities in the Marine Environment

Oceans cover more than 70% of the Earth's surface. They play a critical role in climate regulation and global food supplies and are important foci for the production of energy (both fossil fuel and renewables) that impact our day-to-day lives (Favali & Beranzoli, 2006; Ocean Studies Board, National Research Council, 2000). These connected and dynamic water masses are changing in response to ongoing climate change, yet understanding how local, discontinuous measurements can be upscaled to understand an ocean-scale response is unclear (Favali & Beranzoli, 2006). Traditionally, oceanographic measurements have been made at isolated single-point moorings and/or landers at seafloor, or using arrays of surface floats (Riser et al., 2016). In light of a need to understand the oceans more holistically, there has been a recent upsurge in the deployment of seafloor observatories—monitoring nodes connected by cables (Delaney & Kelley, 2015; Favali & Beranzoli, 2006; Favali et al., 2015; Kelley et al., 2014). Nodes typically feature an array of instruments to make specific measurements of ocean properties and monitor active processes at the seafloor and within the water column at a fixed location (Lintern & Hill, 2010). While the primary purpose of the connecting cables is to provide power and to transmit data in real time, these links could also be used as distributed sensing pathways using DOFS. Therefore, measurement along these cables, existing commercial networks, and bespoke scientific arrays using technology such as DOFS enables sensing of large areas of the ocean floors in a truly distributed manner, thus providing an exciting opportunity to fill in some key gaps (You, 2010). This approach has obvious synergies with scientific programs such as the international Joint Task Force on SMART (Science Monitoring And Reliable Telecommunication) cables that aim to install sensor packages at optical repeaters on the existing global seafloor cable network to measure pressure, temperature, and three-axis acceleration (Howe et al., 2010, 2016).

We now discuss how DOFS could be used to address some specific challenges in ocean science and highlight some recent successful studies (Table 1). We first look at episodic hazards that can cause significant seafloor disturbance (and are therefore likely to be detected most easily by DOFS) and how DOFS can be used to monitor impacts of seafloor hazards and then focus on more subtle variations in ocean conditions (including ocean temperature and acidity) that may be tackled by ongoing and future developments in DOFS technology.

Monitoring Offshore Geohazards

The deep seafloor can be the site of highly dynamic processes. Natural hazards such as earthquakes, seafloor remobilization by tropical cyclones, slope instability (landslides) that may trigger tsunamis, powerful avalanches of sediment (density flows known as turbidity currents), and seafloor expulsion of fluids all pose a threat to critical seafloor infrastructure, including telecommunication networks, oil and gas pipelines and umbilicals, and wind farm interarray cables, as well as to coastal communities (Clare et al., 2017). A growing number of studies (many using legacy or in-service telecommunications cables) are demonstrating the utility of DOFS

TABLE 1

Some recent successful applications of optical fiber sensors to monitor a range of processes that occur on and below the seafloor.

Processes Monitored	Sensing Configuration	Location	Reference
Slope failure/displacement			
Slow seafloor displacement	Bespoke cable: strain measured over <10 km with strain resolution < 1 $\mu\varepsilon$	Offshore San Diego, California	Blum et al., 2008
Slope failure	Bespoke cable: stress measured over 0.5 km	Onshore Yangtze Province, China	Dai et al., 2008
Progressive ground displacement	Bespoke cable: strain measured over tens of meters with strain resolution > 2 $\mu\varepsilon$	Onshore London, UK	Hauswirth et al., 2014
Seismicity			
Earthquake P and S wave detection	Down-borehole deployment of bespoke cable over ~1,000 m used as an interferometer	Onshore California	Blum et al., 2008
Earthquake P and S wave detection	Bespoke cable array over 8,400 m	Onshore Nevada	Wang et al., 2018
Earthquake P and S wave detection	Bespoke cable array: 160-m length	Onshore Fairbanks, Alaska	Lindsey et al., 2017
Earthquake identification and localization	Conventional telecommunications cable: over 15 km	Onshore Reykjanes Peninsula, Southwest Iceland	Jousset et al., 2018
Earthquake identification and localization	Conventional telecommunications cable: over 79 km	Offshore Central Italy	Marra et al., 2018
Fluid flow			
Subsurface pressure and fluid movement detection	Bespoke cable: deployed as a passive hydrophone seafloor array	Offshore Sognefjord, Norway	Goertz & Wuestefeld, 2018
Oceanographic and cryospheric processes			
Lake bed temperature	Conventional telecommunications cable: temperature measured with a spatial resolution of 1 m over 30 km with a temperature resolution of <0.1°C	Lake Geneva, France/Switzerland	Selker et al., 2006
Tracking individual coastal waves	Power cable linking offshore wind farm to the mainland	North Wales, UK	Hartog, 2017
Ice sheet displacement	Down-borehole deployment of bespoke cable over ~1,000 m used as an interferometer	Ice sheet: Siple Dome, Antarctica	Blum et al., 2008

approaches to identify and characterize a range of seafloor hazards (Table 1).

As well as making direct measurements of temperature and strain, existing telecommunications cables may be used as passive seismic arrays. By using existing submarine cable networks, a significant gap in seismic monitoring can be addressed. Most of the Earth's surface is under water, yet most seismic monitoring stations are on land. Jousset et al. (2018) demonstrated how existing telecommunications cables can be used to record earthquake spectra by measuring dynamic strain. Earthquake events have also been observed on a communications cable belonging to Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (Kimura et al., 2018). Field experiments using distributed acoustic sensing along fiber-optic cables in Alaska and California found a high degree of correlation with earthquake measurements acquired with a conventional seismometer and that only a minimal degree of cable-sediment coupling is required for P and S wave detection (Blum et al., 2010). This demonstrated application of fiber-optic cables thus opens up many further possibilities for indirectly measuring other active seafloor processes such as volcanic activity, tsunamis, slope collapses, sediment transport, and fluid expulsion and for detecting a wide range of seismic events, in a similar manner to recent monitoring efforts using hydrophones, ocean bottom seismometers, and broadband seismic arrays (Burtin et al., 2011; Caplan-Auerbach et al., 2014; Clare et al., 2017; Kimura, 2017a, 2017b; Lin et al., 2010; Lindsey et al., 2017; Sgroi et al., 2014). Clearly, calibration will be required for each of these processes and in a range of ocean settings, but the potential application is extremely promising. Other ambitious initiatives are ongoing, such as the use of legacy cables using Brillouin OTDR to determine strain induced by small-scale (mm-cm) displacements at tectonic faults that intersect the seafloor (Gutscher et al., 2017). These initiatives extend previous studies where standard fiber-optic cables were used to measure seafloor displacements due to creep (Blum et al., 2008; Gutscher et al., 2017).

Potential for Monitoring Geohazard Impacts to Offshore Infrastructure

Due to their fast speed (up to 20 m/s) and potential to travel over vast areas of seafloor (up to thousands of kilometers), processes such as landslides and turbidity currents can be particularly damaging for valuable seafloor infrastructure such as cables and pipelines (Pope et al., 2017). While few direct measurements have been made of these processes (Azpiroz-Zabala et al., 2017; Talling et al., 2015), much of what we know about the velocity and run-out distance of these hazards comes from the documented timing and location of sequential telecommunications cable breaks (Burnett & Carter, 2017; Carter et al., 2014). As the global network of telecommunications cables transmits more than 99% of all digital data traffic worldwide (including the Internet), better understanding the threat posed by such processes is of global importance (Kelley et al., 2014). Recent measurements have revealed that not all of these seafloor processes will necessarily cause a cable or pipeline to rupture, however (Clare et al., 2017). Instead, they may cause drag, loading, and/or displacement on the structure (e.g., Dai et al., 2008). These pronounced effects would all be recorded as localized and variable strain along an optical fiber; hence, DOFS sensing could provide new insights into the timing, duration, magnitude, and spatial extent of such seafloor events with unprecedented spatial coverage (Clare et al., 2017; Talling et al., 2015) as well as much needed information on the integrity of the seafloor structure itself during these hazardous events and over its engineering lifetime (20–40 years; Hartog, 2017).

Cables are often the potential weak points in offshore wind developments. Fibers are commonly embedded in electrical energy interconnectors and in the cables transmitting the power generated by offshore wind farms back to land. These fibers have already been used to detect the occurrence of damage (e.g., from fishing vessels; Hartog, 2017) using distributed strain and/or vibration sensing. This locating capability enables accelerated repair or intervention. Using existing fibers for the detection of anthropogenic, natural hazards or incipient structural damage is particularly attractive because it provides the potential for an early warning system, for example, ensuring that buildup in strain due to repeated impacts by hazards such as turbidity currents does not reach a critical threshold. In such a situation, mitigation measures (e.g., reconfiguration of cables on the seafloor) could be taken before a break occurs, thus minimizing any losses in connectivity.

A distributed vibration sensor connected to a subsea energy cable was able not only to reveal the sea state but also to track individual waves (Hartog, 2017).

Addressing the Challenges of Measuring Ocean-Wide Climate Change

There is much uncertainty in how temperatures are changing close to seafloor due to the paucity of monitoring stations globally; hence, the possibility of temporally continuous and spatially distributed measurements using DOFS is appealing. Legacy fiber-optic telecommunications cables have been used to make measurements of submarine processes and temperature in Lake Geneva, where high-resolution daily fluctuations in lake-bed temperature were recorded to a resolution of 0.1°C (Selker et al., 2006). While such lacustrine and shallow water environments may show >1°C daily temperature variations, we recognize that similar short-term background variability in deep-sea temperature may be at the limits of detection using DOFS systems (10–20 mK); longer-term (annual to decadal) changes in ocean temperature (in the order of 0.1–0.5°C rise per decade; e.g., Bethoux et al., 1990; Danovaro et al., 2004) are well within the measurement capabilities of DOFS, however. Longer-term variations are key inputs to future climate models. Furthermore, ephemeral processes in the deep sea may induce much greater short-lived temperature variability (>1°C) that is more easily detected, such as that due to cascading of cold, dense shelf water (Canals et al., 2006); influx of warmer water introduced by turbidity currents (Xu et al., 2010); or sudden seafloor emission of warmer subsurface fluid (Von Damm et al., 1995). In the case of distributed temperature sensors, marinized systems have been deployed for research purposes in, for example, subsea methane hydrate production (Kanno et al., 2014; Sakiyama et al., 2013) and studying the heat emitted by mid-ocean ridges (Nishimura et al., 1995). While some distributed chemical sensors have been demonstrated and developed, they are in general suitable for benign environments such as inside buildings. While advances in cable-connected seafloor systems now enable high-resolution discrete measurement of CO_2 at specific deep-sea locations (Mihaly, 2010), there is at present no truly distributed sensing capability for CO_2 content or pH suitable for deployment on the seabed. In the short term at least, it will be necessary to rely on discrete measurement at seafloor observatories or proxies based on the distributed measurements of physical quantities.

Development of Bespoke Cables for Distributed Sensing

Notwithstanding the benefits of repurposing existing cables for sensing, dedicated sensing cables can offer improved sensitivity and discrimination between measurands, for example, cable designs including fibers that are strain-coupled to the cable structure and others that are packaged in loose tube. In this design, the temperature and strain are measured independently using Brillouin OTDR to interrogate one of each type of fiber. The strain-relieved fibers measure only temperature, and this information is then used in its own right and to correct the measurements on the strain-coupled fibers that respond to temperature and strain (Strong et al., 2008).

Although distributed vibration measurements are found to respond well to small, dynamic strains even in loose-tube packages (Mullens et al., 2010; Strong et al., 2009), it should be noted that the distributed vibration measurement is in fact a measure of dynamic axial strain (Dean et al., 2015, 2016). As a result, the measurement is insensitive (Papp et al., 2016) to compressional acoustic waves arriving at right angles from the fiber axis. Omnidirectional cables have been designed (Kuvshinov, 2016) and tested (Hornman et al., 2013), in which the fiber is wrapped helically around a central former, with the fiber segments being exposed roughly equally to components of the sound wave arriving from any direction. In seismic applications, there is also an interest in multicomponent sensors; to this end, cables with specific sensitivity to one geometrical component and several concepts have been proposed, with some based on imposing particular patterns to the fiber in the cable (Kragh et al., 2012; Hartog et al., 2014), including inertial mass (Crickmore & Hill, 2014; Den Boer et al., 2012), or attaching the fiber periodically along the cable, allowing it to vibrate between attachment points (Farhadiroushan et al., 2015).

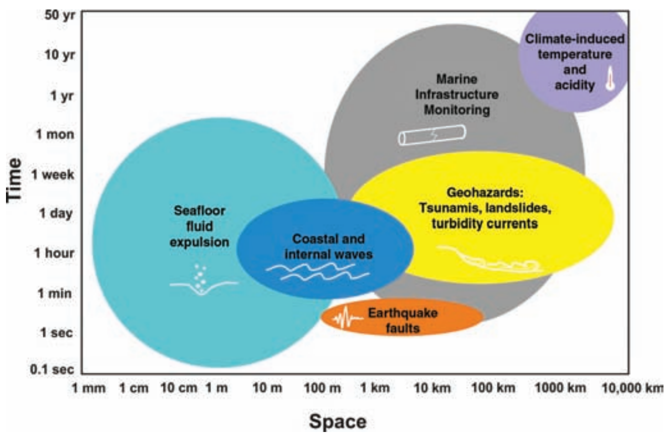
Concluding Observations

DOFS is a proven set of technologies that now allows us to make high-resolution measurements of key variables for both structural health monitoring and sensing the natural environment. A growing number of studies and projects are proving how powerful the technique can be in the marine environment as passive sensor arrays (e.g., seismicity), in measuring the direct impact caused by dynamic processes (e.g., turbidity currents), and in ambient conditions (e.g., subtle changes in temperature).

Recent strides forward in DOFS sensing technology enable the use of existing and legacy infrastructure (of which there is a considerable amount of >1 Gm), thus adding a significant value to already laid networks such that we can better understand scientific, societal, and industrial opportunities and risks. Further technological advances in interrogation, cabling,

FIGURE 3

Space-time relationship for various processes across the range of scales in the marine environment that have been successfully monitored using DOFS, as detailed in the text and in Table 1. Adapted from Lampitt et al. (2010).



and installation methods will enhance the capability of newly installed systems to have better performance and a longer range and the ability to profile more measurands.

A holistic approach is required to understand the oceans dynamic response to global warming, quantify the risks posed by hazards, and ensure that critical global networks (that supply power and communications) continue to run safely and effectively. The time scale and spatial range of the processes that DOFS could contribute to monitoring are mapped in Figure 3. The ability of DOFS to perform continuous temporally and spatially resolved sensing across large distances of the seafloor at low power and cost offers a new and complementary approach to traditional oceanographic monitoring. Adoption of DOFS technology provides a valuable opportunity to fill in spatially extensive gaps between existing isolated oceanographic monitoring stations, to unlock additional potential of cabled seafloor observatory networks, and, in turn, to deepen our understanding of the world's oceans.

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PAPER

Foundational Experiences and Recent Advances in Long-Term Deep-Ocean Borehole Observatories for Hydrologic, Geodetic, and Seismic Monitoring

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ABSTRACT

For nearly three decades, various phases of the scientific Ocean Drilling Programs have deployed sealed-hole observatories in deep-ocean boreholes for long-term subseafloor monitoring to address a range of hydrologic and geodynamic objectives. We summarize the scientific motivation for these observatories and review some important early results from those installed in young oceanic crust and subduction zones. We also summarize the evolution of the borehole observatory designs and associated instrumentation, from simple single-interval installations with autonomous low-rate temperature and pressure monitoring to recent multiple-zone installations with sophisticated downhole instrument packages connected to seafloor cabled networks that provide power and high-rate, real-time data access. We emphasize recent advances, illustrated with example data drawn mainly from transects of borehole observatories offshore Japan and Cascadia. These examples illustrate the value of borehole observatory data in resolving a wide range of crustal geodynamic responses from long periods of gradual geodetic change and accumulation of stress to episodes of rapid deformation associated with both seafloor spreading and subduction processes.

Keywords: borehole observatories, marine geodesy and geodynamics, marine seismology, ocean crustal hydrogeology and deformation, long-term subseafloor monitoring

Background

A range of goals in the earth sciences requires long-term observations, and this is certainly true in the study of crustal geodynamics. Major deformational episodes take place as long periods of gradual geodetic change and accumulation of stress, punctuated by episodes of rapid deformation related to such things as seafloor spreading "events" and earthquakes at transform and convergent plate boundaries. This behavior is in a way analogous to the "punctuated equilibria" used to characterize biological evolution (Eldredge & Gould, 1972). The times that separate seismic and other geodynamic events range from 1 to several years for slow earthquakes, from several years to decades for earthquakes along transform faults and eruption events at seafloor spreading centers, and decades to centuries for damaging earthquakes at many subduction zones. Clearly, to study both the gradual changes in stress, strain, and hydrologic state between events, and the catastrophic events themselves require very long-term, continuous observations of relevant parameters. Land-based seismic and geodetic observations have provided solid guidelines for the typical frequency of events and for the locations where further studies can be sited with the greatest effect, but they do not provide the resolution required for characterizing phenomena that occur in offshore locations, such as at mid-ocean ridges and subduction zones. Seafloor observational instrumentation, including commonly used ocean bottom seismometers and pressure sensors, and benchmarks that are acoustically linked to sea-surface GPS receivers (Bürgmann & Chadwell, 2014) and linked in pairs by fiber-optic strain sensing cables (Zumberge et al., 2018) are being used to a great advantage. Over the past three decades, it has also been learned that observations in boreholes provide highly complementaryand often unique and intrinsically valuable data.

Some early seafloor borehole monitoring experiments were initiated to study crustal deformation and to improve the quality of seismic observations. With limits imposed by power consumption, battery capacity, and site servicing, however, experimental lifetimes were relatively short compared to event recurrence intervals, which themselves were poorly defined. Most experiments were set up with relatively short-term objectives, for example, to document the thermal state of formations in the absence of drilling perturbations, to track seismic wave arrivals below the dominant influence of noise induced by ocean currents and short-wavelength pressure perturbations, and to define the natural hydrologic state of subseafloor formations. Examples of early borehole installations included downhole temperature sensors, seismometers, and strain meters (Araki et al., 2004; Shipboard Scientific Party, 1991, 2000; Stephen et al., 2003). In most instances, long-term observations were planned, but multiyear operational lifetime was technically challenging, and the quality of observations was compromised by the flow of water into or out of the formation via the open holes.

Three Decades of Sealed-Borehole System Developments

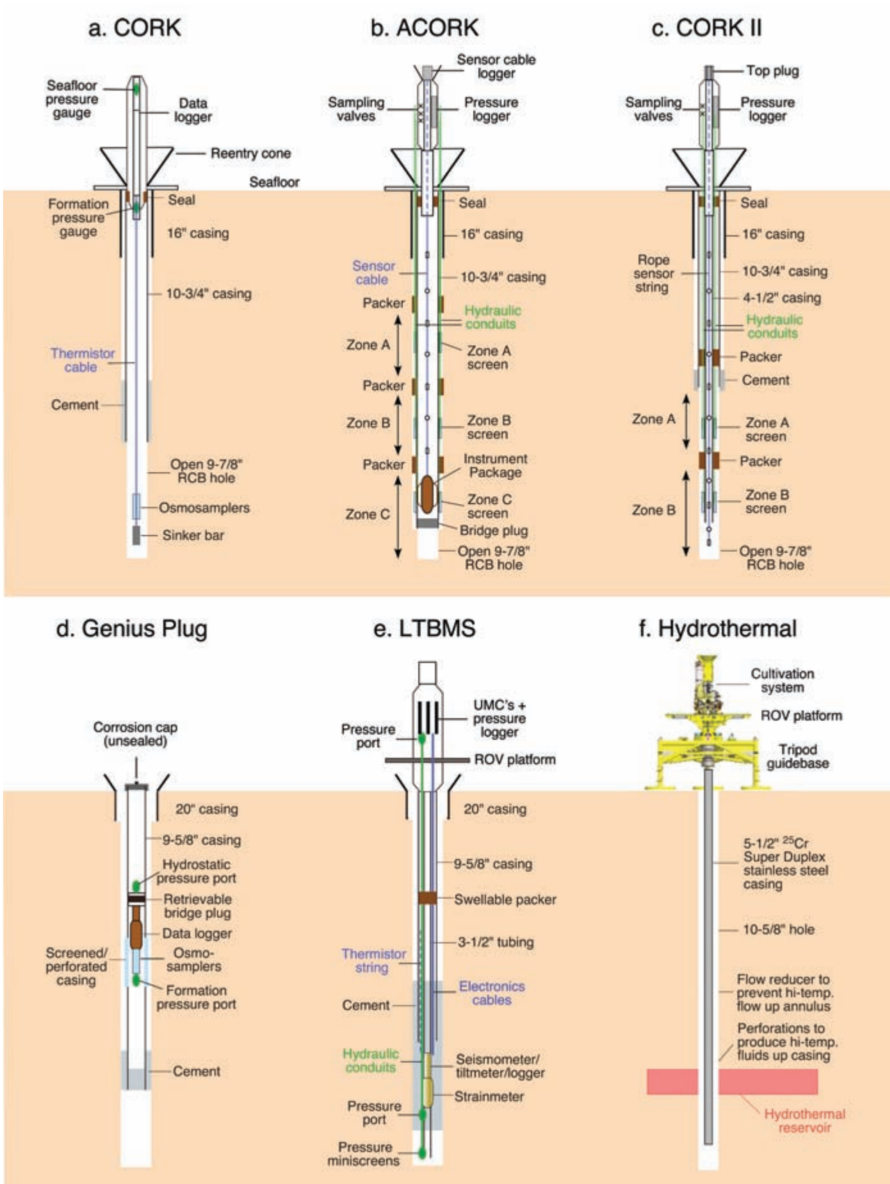
One of the most useful technical lessons learned from early Ocean Drilling Program (ODP) borehole observatory attempts was that, if holes were sealed after drilling, their recovery from drilling perturbations would permit observations of the natural formation thermal and hydrologic states. Hole sealing was the key element of the first "CORK" hole completion system (named accordingly "Circulation Obviation Retrofit Kit"), developed for first use in the sediment-filled rift valley of the northern Juan de Fuca Ridge (Davis et al., 1992). In the case of this and other early CORK experiments, experiments survived for many years, and they led to observations of natural variations in physical and chemical states, variations that were intrinsically interesting and that provided motivation and justification for more sophisticated multidecadal monitoring experiments that followed.

In the first experiment that began in 1991, two holes were drilled, sealed, and instrumented for fluid sampling and long-term observations of pressure and temperature. Both holes intersected highly permeable igneous rocks buried by a thick, extensive, and low-permeability layer of turbidite sediment. The igneous formation intersected by one of the holes was strongly sub-hydrostatic (−250 kPa relative to the local geothermal hydrostat), and the other was strongly super-hydrostatic (+200 kPa). Prior to sealing, downhole and uphole flow was unchecked, making fluid sampling and many *in situ* measurements meaningless. A large number of holes drilled in similar settings have told the same story: The local pressure state is set in the context of the hydrologic structure by thermal buoyancy forces; where sealed, the holes can provide valuable information about the formation thermal, chemical, and hydrologic states, and where not, uphole or downhole flow was often rapid and persistent (a fact known from logging results completed much earlier; e.g., Hyndman et al., 1976), massive perturbations occurred over long periods of time (Becker et al., 2001, 2004), and flow-induced seismic noise was generated over a broad bandwidth, making the deep subseafloor environment less quiet than it ideally could be (e.g., Crawford et al., 2006). Holes completed in sedimentary formations pose a different challenge. Low permeability prohibits rapid flow in unsealed holes, but even small amounts of discharge or recharge can cause large and long-lived changes in pressure. Hence, for a variety of reasons, a critical element to the success of any borehole observatory installation is proper hydrologic sealing.

A range of schemes has evolved since the early borehole observatory installations, with increasing flexibility for monitoring pressure and temperature at multiple formation levels and for hosting instruments that require physical contact with the formation, such as seismometers, tilt sensors, and strain meters. The earliest and simplest original CORK configuration (Figure 1a) sampled pressure in an open-hole interval, below casing cemented into the formation. This provided a means to deploy downhole thermistor cables and fluid samplers but had two significant limitations. With the borehole seal situated at the seafloor, pressure observations were limited to a single zone, and signals were transmitted to the formation pressure sensor mounted at the wellhead via the full volume of water inside the casing. Roughly 10 years later, scientists and ODP engineers developed two multizone designs, the Advanced CORK or ACORK and the CORK II (Figures 1b and 1c). Both utilized inflatable packers to isolate separate zones intersected by the holes. For the ACORK, casing packers were added to the standard casing system, and formation

FIGURE 1

CORK sealed-hole evolution schematic, showing the "original CORK" that provided measurements in a single formation interval (a); the ACORK that includes multiple formation screens for pressure monitoring and leaves an empty casing, sealed at the bottom, for instrument installations (b); the "CORK II" that allows instruments and fluid samplers to be installed within multiple packed-off intervals established below the primary casing string (c); the "Genius Plug" that permits single-level pressure and temperature monitoring and fluid sampling when there is a lapse of time between initial drilling and casing operations and later hole deepening (d); the "LTBMS" in which a long instrument string is cemented into the formation in open hole below casing (e); and a temperature-hardened adaptation of the basic CORK concept for controlling and sampling high-temperature hydrothermal fluids from super-hydrostatic formations (f).



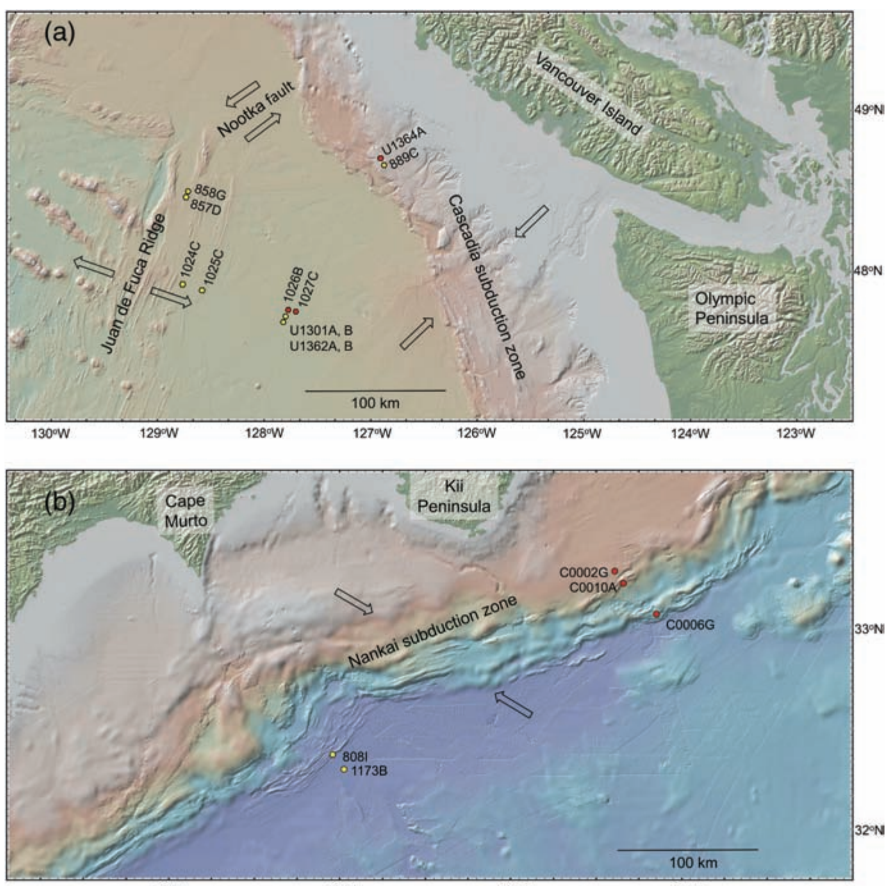
pressure signals were brought from screens mounted on the outside of the casing to wellhead valves and sensors via rigid hydraulic umbilicals. The CORK II featured a 4.5-inch–diameter casing string deployed into a hole established with a reentry cone and 10¾-inch casing; the smaller casing incorporated inflatable and swellable packers, screens, and hydraulic umbilicals running from multiple zones to the surface. Both the ACORK and CORK II allow for sensor strings deployed down the inside of the casing. Further details of these systems are reviewed in Becker and Davis (2005).

More recent designs have included the simple, autonomous "Smart Plug" for temporary monitoring (and fluid sampling in the augmented "Genius Plug") in holes later to be deepened and the complex Long-Term Borehole Monitoring System (LTBMS), built and maintained by JAMSTEC (Japan Agency for Marine-Earth Science and Technology) with extensive downhole instrumentation. The former integrates a mechanically set, removable bridge plug to seal the hole and an autonomous data logger with sensors/samplers mounted below (Figure 1d; Kopf et al., 2011). The plug was set just above an interval of interest where the casing has been perforated and screened. The Smart Plug included hydrostatic and formation pressure ports above and below the bridge plug, respectively; fluid samplers driven by osmotic pumps were added in the Genius Plug for long-term fluid sampling in the zone isolated by the bridge plug. The LTBMS (Figure 1e) is structurally similar to the CORK II but includes downhole instrument packages and electronic connections to the wellhead (Kyo et al., 2014). A simplified version of this observatory design was deployed during the Japan Trench Fast Drilling Program (JFAST), with a string of autonomous temperature loggers suspended inside the borehole casing (Fulton et al., 2013). Also built around this model is a system to bring hot hydrothermal fluid to the seafloor in a controlled manner and to extract hydrothermal minerals (Figure 1f; Akiyama et al., 2016). The system is designed to withstand temperatures up to 315°C and includes a flow meter within the casing and multiple removable microbial culturing cells supplied by valved plumbing.

One other noteworthy development for the advancement of observatories has been a system to suppress vortex-induced vibrations during deployments (Kyo et al., 2014). This is particularly important in settings where strong currents and rough weather are present. Drill pipe strumming induced by the Kuroshio current has often had a severe impact on installations off eastern Japan.

FIGURE 2

Maps (from GeoMapApp) showing locations of a sampling of ODP boreholes where sealed observatories have been installed, including the Juan de Fuca Ridge eastern flank and the Cascadia subduction zone (a) and the Nankai subduction zone (b). Holes that have been connected to the ONC/NEPTUNE and DONET fiber-optic cable systems are highlighted in red.

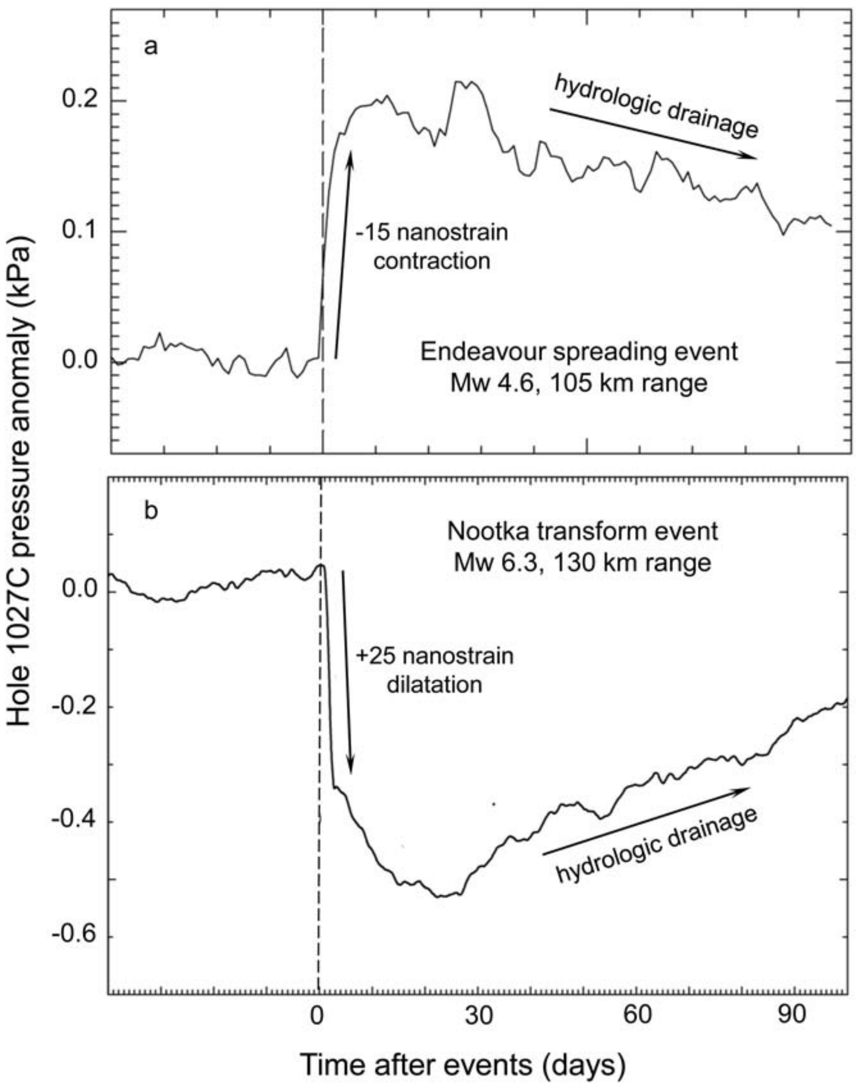


Unexpected Results From Early Experiments

The earliest CORK observatory experiments focused on hydrothermal circulation in sedimented mid-ocean ridge and ridge flank settings (Figure 2a). Observations showed the uppermost igneous crust to be nearly isothermal over large lateral distances and despite large local variations in insulative sediment burial thickness. This suggested high rates of fluid flow within the crust and, together with the very small lateral gradients in observed pressure (a counterintuitive conclusion given the large pressure differences vertically across the resistive sediment layer), allowed a determination of igneous layer permeability that was characteristic over a lateral scale of several kilometers. Some of these same boreholes were also used in "pumping" experiments, with both artificial and natural perturbations induced by nearby drilling, tidal loading, and transient strain.

FIGURE 3

Reactions of formation pressure at ODP Hole 1027C (location in Figure 2a) to regional strain associated with a seafloor spreading event on the Endeavour Segment of the Juan de Fuca Ridge, 110 km to the west on June 8, 1999, and to a strike-slip earthquake on the Nootka transform fault 130 km to the north on October 6, 1996 (plot axes are shown relative to event times). The relationship of volumetric strain to pressure is established by the formation elastic properties defined by the reaction of formation pressure to seafloor tidal loading (e.g., see Figure 6a). The sign of the pressure transients is consistent with the strain that would be predicted from fault slip in each case (compressional in a, dilatational in b), but the signals are larger than expected (particularly in the case of the ridge event), suggesting low seismic efficiency. The strain-induced pressure changes at this site are not maintained; pressures return to static values (set by hydrothermal buoyancy forces) in less than 1 year as a result of hydrologic drainage through the igneous crust laterally beneath the sediment seal to locations of igneous outcrops near the Juan de Fuca Ridge axis.

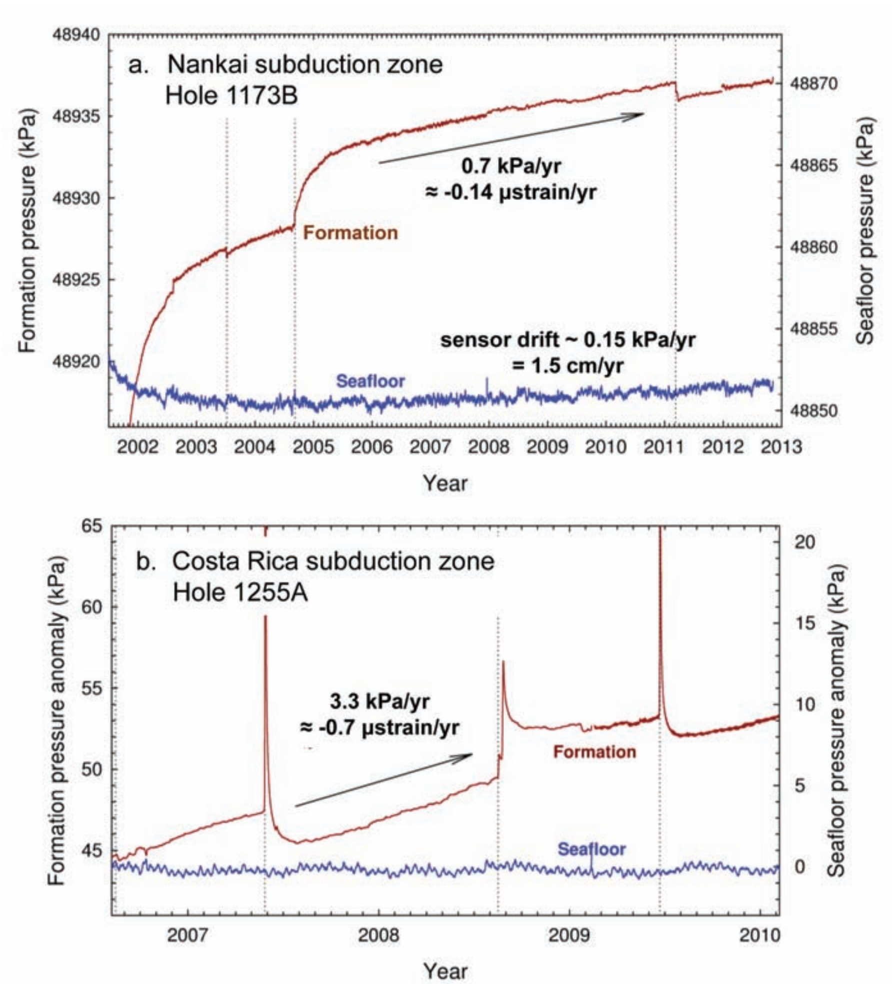


These added further constraints on igneous crustal permeability over scales up to 100 km, on the high degree to which permeability is scale dependent, and on the low "effective porosity" that hosts the bulk of fluid flow—in what was found to be a highly heterogeneous and hydrologically anisotropic formation (Becker & Davis, 2004; Davis et al., 2001; Neira et al., 2016).

In some instances, monitoring continued for sufficiently long periods to capture transient pressure and temperature signals associated with earthquakes, some up to several hundred kilometers away. Formation response to tidal loading at the seafloor provided a "calibration" of formation elastic properties, and this allowed the pressure transients to be used as quantitative proxies for local and regional strain (Figure 3). This new utility formed the foundation for a number of experiments that followed, set up specifically to track secular and transient strains through the interseismic, coseismic, and postseismic parts of earthquake cycles. This was particularly effective in holes completed within thick sedimentary formations, where transient pressures are retained for hundreds to thousands of years. In such instances, pressures track strains reliably not only over short times during and shortly after an earthquake but also over long periods between earthquakes (Figure 4; Davis et al., 2013, 2015). This contrasts with observations in igneous formations, where the time constant for hydrologic drainage over many tens of kilometers lateral scale is found to be very short (days to months, depending on the distance of the drainage path to seafloor basement outcrops; see Figures 2 and 3). While seemingly indirect, such an approach of using pressure as a proxy for strain is valuable from a number of perspectives. An important consideration is that it is simple; pressures are transmitted to the wellhead hydraulically, with sensors and other electronic components located in the thermally benign and accessible location of the wellhead. Second, with reasonable formation permeability and low

FIGURE 4

Long-term seafloor and formation pressure records from ODP Hole 1173B in the Philippine Sea plate being subducted at the Nankai subduction zone (a; location in Figure 2b) and Hole 1254A in the over-thrusting subduction prism off Costa Rica (b). At Nankai, recovery from drilling (in mid-2002) is seen to have taken nearly 2 years. Stepwise changes in pressure (vertical dashed lines) in the incoming plate at Nankai and impulsive transients in the overriding prism at Costa Rica occur at the times of local slow slip events that are in some cases triggered by regional earthquakes. These anomalies are superimposed on background secular trends that are inferred to reflect long-term strain accumulation caused by interplate convergence. At Costa Rica, the trend is substantiated by formation-sensor offset checks at times of submersible visits; a check at Nankai is planned for 2019.



measurement-system elastic compliance, the reaction of the formation to strain is derived from a large formation volume. This spatial averaging greatly reduces the sensitivity to local heterogeneity that affects strain sensors. Third, instrumental drift can be defined and corrected for (as discussed below).

Observations like those illustrated in Figures 3 and 4 led to a number of new insights, including the following: (1) stepwise changes in pressure are common at the times of earthquakes and slow slip events at divergent, convergent, and transform plate boundaries. (2) The signs of these changes are consistent with the polarities of volumetric strain expected from the source events (negative when dilatational; positive when contractional). (3) The magnitude of change indicates strain that is larger, often much larger, than predicted given the distance to and seismic moments of the events. This leads to estimates of the seismogenic inefficiency of slip, that is, the proportion of slip that does not generate seismic waves. (4) In some instances, slip occurs slowly and aseismically and propagates along faults very slowly, of the order of a few kilometers per day. (5) Local slip at subduction thrusts can be triggered by stress imposed by seismic ground motion or the change in static stress generated by distant large earthquakes. (6) Where monitoring horizons are hydrologically well isolated, interseismic strain accumulation can be tracked.

Broadening the Scope of Observations: Expanding Resolution, Sampling Frequency, and Sensor Types

Through the nearly three decades since the deployment of the first borehole observatories, significant improvements have been made that have improved sensor reliability and longevity, and increased measurement resolution and bandwidth. In the case of temperature measurements, improved jacketing and potting materials has eliminated problems initially experienced at high temperatures with leakage in cables where thermistors are connected electrically to the wellhead. Where shorter-term deployments were planned and physical recovery was possible, experiments have successfully utilized miniature stand-alone temperature sensor/logger elements attached to strength members. In the case of pressure measured with

Paroscientific Digiquartz sensors, resolution was initially limited to ca. 1 ppm of full-scale pressure (equating to roughly 40–100 Pa in typical water depths and anticipated maximum formation pressures), and memory, power, form-factor, and submersible and remotely operated vehicle (ROV)-based download constraints limited sampling intervals to 5–10 min. In 2004, 1-ppb resolution of the output frequency of the commonly used Paroscientific quartz absolute pressure sensors was realized through the use of a precise fractional-period counter system (PPC, developed with John Bennest of Bennest Enterprises, Ltd.). This device was capable of resolving pressure changes 100 times smaller than previously possible (i.e., equivalent to 0.04–0.1 mm of water head) at sampling frequencies up to 1 sample per second (s.p.s.). Equivalent gains in resolution have been realized subsequently by commercially available counters built by Paroscientific, Inc., and RBR Ltd., with sampling frequencies of 20–40 s.p.s. Logistical limits on sampling frequencies for autonomous deployments remain, although gains were realized during two experiments through the use of an optical modem, which proved to be capable of transmitting data at rates up to 10 Mbits per second over a range of up to 100 m using a transceiver deployed on a conductivity/temperature/depth (CTD) cable (Farr et al., 2010).

The most significant technical augmentation for long-term borehole monitoring experiments has come from the use of offshore fiber-optic cable systems that provide power, communication, and precise timing. To date, six borehole observatories have been connected to two such systems; three to the NEPTUNE (Northeast Pacific Telemetered Undersea Networked Experiment) system installed across the Cascadia subduction zone and Juan de Fuca Ridge, operated by ONC (Ocean Networks Canada; ODP/IODP Holes 1026B, 1027C, and U1364A); and three to the DONET (Dense Oceanfloor Network System for Earthquakes and Tsunamis) system installed across the Nankai subduction zone, operated by NIED (National Research Institute for Earth Science and Disaster Resilience; IODP Holes C0002G, C0006G, and C0010A). These all employ Bennest PPC electronics with Paroscientific quartz pressure sensors. Data are transmitted in real time, time stamped, and archived by ONC and JAMSTEC. Onboard lithium/thionyl chloride batteries are capable of operating the loggers for several years in the event of a loss of cable power (when the units automatically switch to a 1-min sampling interval and consume power at a reduced average rate of roughly 4 mW) or at times after deployment and prior to being cable connected as in each of the cases cited above.

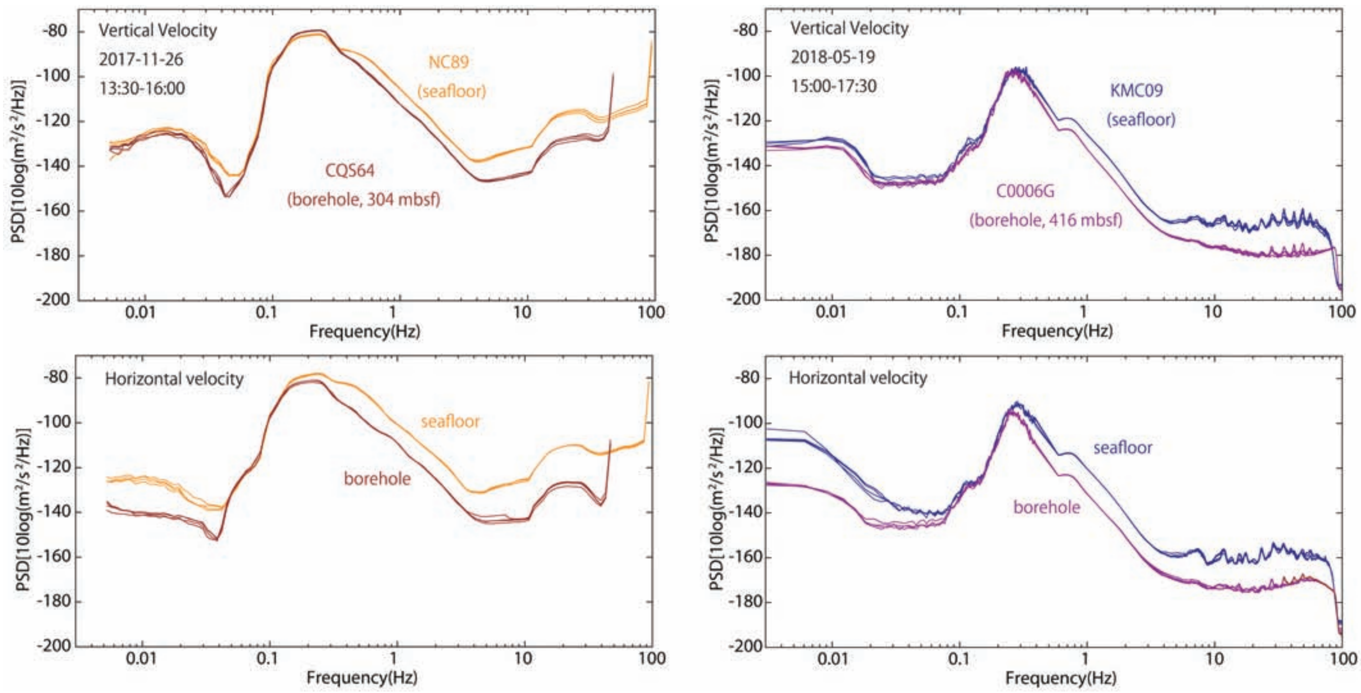
Building on previous efforts to deploy seismometers and strain meters in deep-ocean boreholes, a concerted effort has recently been put into taking advantage of the sealed-hole configuration of CORKs to eliminate flow- and thermally induced noise and to complement pressure observations. Two primary examples are the LTBMS described above—now in operation in the three holes connected to the DONET cable that span the Nankai subduction zone off Kii Peninsula (Figure 2b; Araki et al., 2017; Kinoshita et al., 2018)—and a downhole instrumentation system developed at the Woods Hole Oceanographic Institution, deployed at the Cascadia subduction zone Hole U1364A, and linked to the ONC cable network (Figure 2a; McGuire et al., 2018).

In the former system, an instrument assembly is grouted into the formation below a section of 9 5/8" outside diameter (o.d.) solid steel casing (Figure 1e). The instrument assembly comprises short-period geophones, a broadband seismometer, tilt sensors, strong-motion accelerometers, and a volumetric strain sensor, along with a thermistor string with sensors distributed within and above the formation assembly. Hydrologic sealing and mechanical coupling of the instruments to the formation are accomplished by injecting cement around the instrument and up to a level above the base of the casing and by sealing the pipe that carries the instrument assembly within the larger borehole casing with a swellable packer. As in the case of most CORKs, pressures are monitored by sensors mounted at the seafloor that are hydraulically connected to permeable screens in the formation via thick-walled ¼-inch o.d. stainless steel tubing.

At Cascadia, the instrument package is installed inside the 10¾-inch solid steel casing (Figure 1b). The package comprises a medium-bandwidth three-component seismometer, two (redundant) tilt meters clamped inside the casing just above the bottom casing plug, and a thermistor array with sensors distributed along the full depth of the hole. Pressures are monitored with sensors at the seafloor, via permeable screens that are wrapped around the outside of the casing, that is, in the ACORK format (Figure 1b). While a direct measurement of strain is not possible through the casing, this configuration allows the internal sensor package to be removed, modified, and replaced by wire line. It also ensures good hydrologic sealing and provides a large contact area for

FIGURE 5

Comparison of background velocity spectra measured at the seafloor and in IODP Holes U1364A at Cascadia (left) and C0006G at Nankai (right) in the outer subduction zone accretionary prisms. Seafloor seismometers are buried just below the seafloor; borehole seismometers are positioned 300 and 416 mbsf, respectively. The most prominent peaks reflect microseismic energy generated locally and elsewhere by ocean waves. The spectra were derived from three half-hour segments of data recorded in Hole U1364A during a storm and in Hole C0006G during a calm period.



pressure transmission from the formation to the sensors.

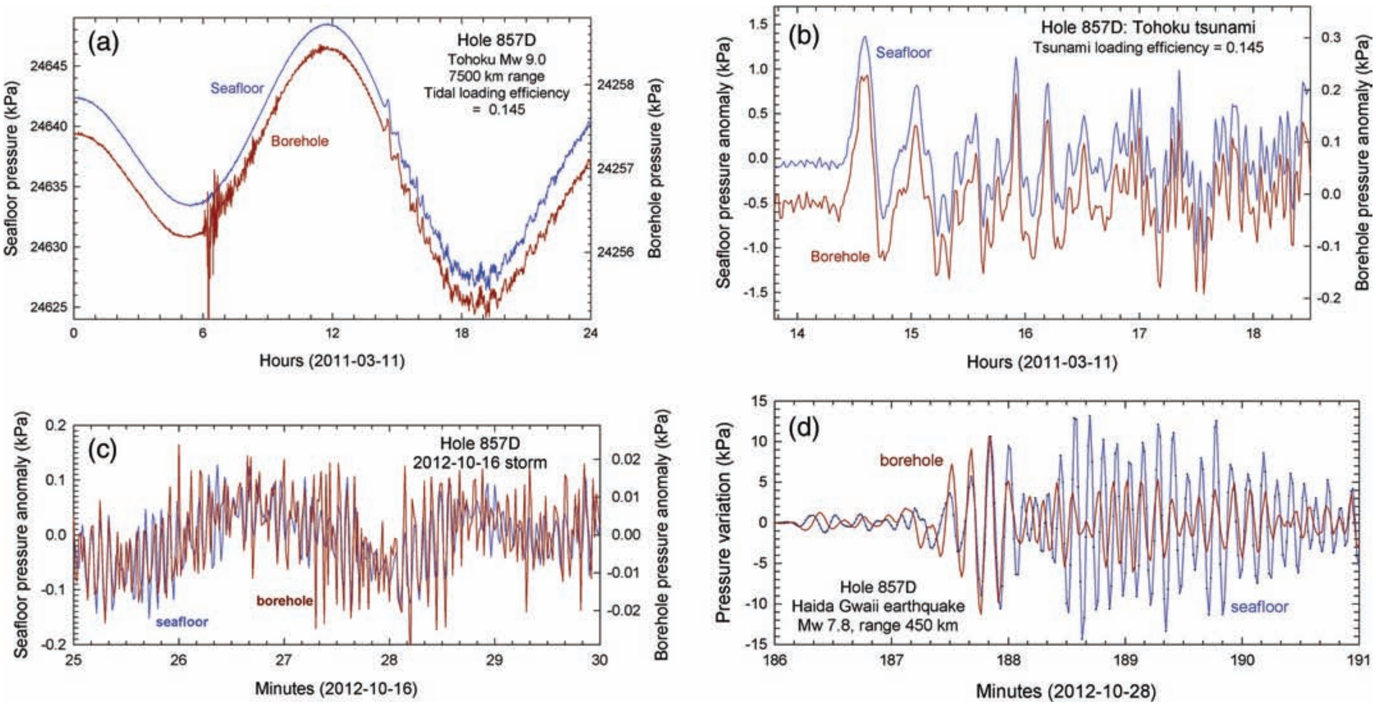
A primary advantage gained by installing seismometers and tilt sensors in boreholes is illustrated in Figure 5, which compares background seismic signals recorded several hundred meters below the seafloor with those recorded simultaneously at the seafloor. Background signal levels seen by the borehole instruments are 5–10 dB lower than those at the seafloor across most of the seismic frequency bands. This is particularly true in the case of the horizontal channels.

A Variety of Signals From a Common Source: The Tohoku-oki Earthquake

In 2011, multiple borehole observatories captured signals from the devastating Tohoku-oki earthquake off the east coast of Japan. These included ODP Hole 857D in the northeastern Pacific, 7,500 km away (Figure 2a), and the four boreholes that had been established by this time at the Nankai subduction zone roughly 800 km from the earthquake epicenter (Figure 2b). Roughly 16 months after the event, IODP Hole C0019D was drilled directly into the seaward part of the Tohoku fault zone itself and instrumented with an array of temperature sensors. The observations from all of these sites serve well to illustrate the broad utility of borehole monitoring for geodynamic studies. The most distant observations at Hole 857D were made when a combination of precise period counters, a large battery, and a high-speed optical transmission system (described above) had been installed in "piggyback" mode, providing high-resolution seafloor and formation pressure data—20 years after this the first CORKed hole was established. These data reveal the substantial hydrostatic pressure present at this site as well as the formation response to variable loads imposed by ocean tides (Figure 6a), by seismic waves and the subsequent tsunami from the 2011 Tohoku-oki earthquake (Figures 6a and 6b), by ocean infragravity waves and microseisms generated by a local storm (Figure 6c), and by seismic surface waves from a large local earthquake (Figure 6d). The relationship between the seafloor and formation signals over the large range in frequency and wavelength of these loading forces provides valuable constraints on formation elastic and hydrologic properties (e.g., expanding the scope of methods presented in

FIGURE 6

High-resolution observations made in ODP Hole 857D (location in Figure 2a) that reveal the large average sub-hydrostatic pressure present at this site and the formation response to external loads imposed by oceanographic loading and by the teleseisms and tsunami generated by the Tohoku-oki earthquake on March 11, 2011. Relative scaling of formation (right *y* axis) and seafloor pressures (left *y* axis) is adjusted to reflect the 1-D elastic loading efficiency, which is similar at signal periods ranging from tides (12–25 h) (a), tsunami (5–30 min) (b), and ocean infragravity waves and microseisms generated by local seas and swell (c). The relationship of seafloor and formation pressure differs for seismic surface waves (d), which produce formation strain that is not reflected by seafloor pressure.

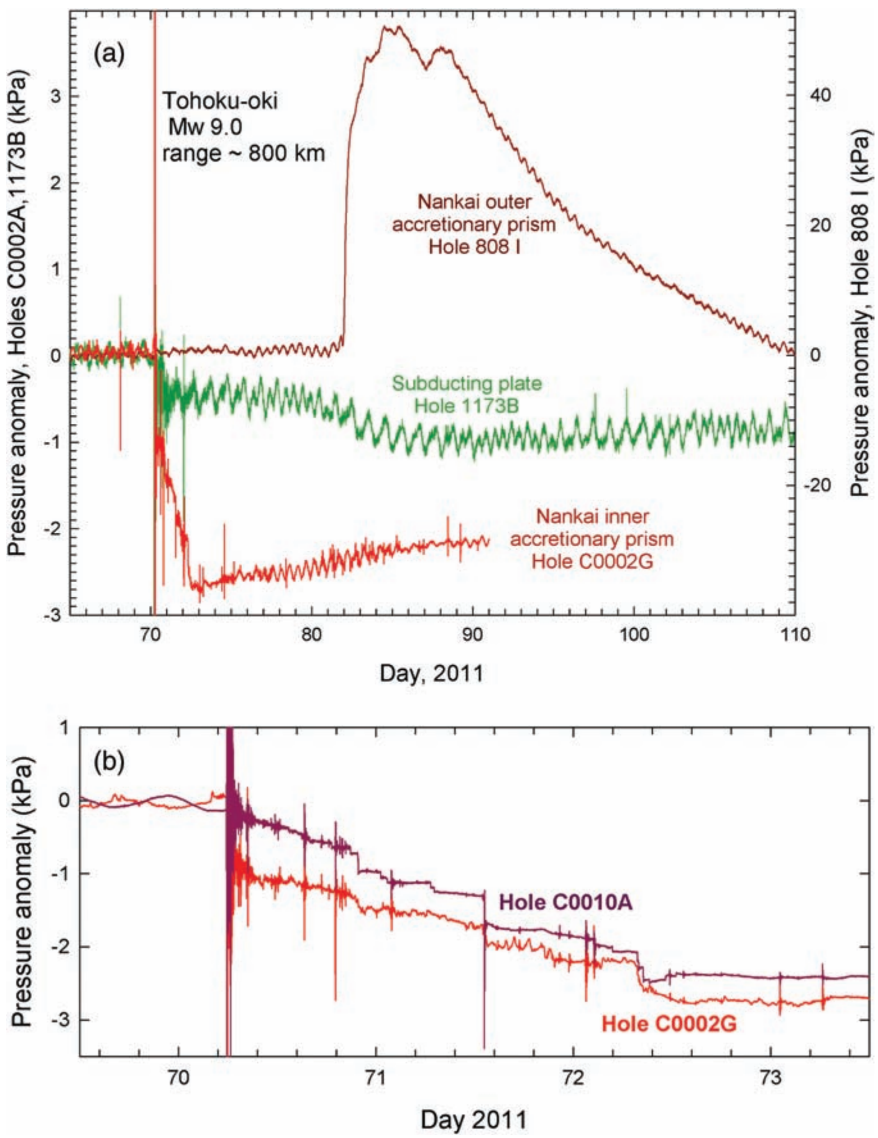


Crawford et al., 1991, and Davis et al., 2000).

Signals from the sites closer to the Tohoku earthquake are interesting from a different perspective. The records shown in Figure 7 were captured by the first LTBMS installation, completed in Hole C0002G; by a preliminary Genius Plug in Hole C0010A (both near the updip end of the Nankai subduction fault seismogenic zone), and by older ACORKs in the outer subduction prism (Hole 808I) and the incoming Philippine Sea plate (Hole 1173B). While the composite "transect" crossing this subduction zone that these sites constitute is offset by 150 km, the nature and timing of the pressure anomalies highlight a characteristic behavior of this subduction fault, namely, triggered and sometimes spontaneous slow slip. The coseismic pressure anomalies seen at Holes C0002G are inferred to have been caused by local slip on or near the seaward limit of the seismogenic zone, stimulated by dynamic shear loading imposed by large Tohoku-oki seismic surface waves (Araki et al., 2017). An expanded view of the records from Holes C0002G and 0010A provides constraints on the evolution of local slip. Decreasing pressure, local dilatational strain, and, by inference, slip on the underlying subduction fault continued for 2 days after the earthquake, with several discrete stepwise events superimposed. Slip like this is likely to have occurred at a similar position landward of the other two holes as well, with the slip then propagating seaward, reaching the prism toe at the location of Hole 808I 11 days after the triggering earthquake and causing the large contractional signal seen there and the small dilatational signal seen in the incoming plate at Hole 1173B. The stepwise coseismic change in pressure at Hole 1173B probably reflects the regional extensional strain associated with triggered local slip initiated several tens of kilometers landward; the magnitude of the step is too large to be a result of regional static strain generated by the Tohoku-oki earthquake itself. Other events like this, with both triggered and spontaneous slip propagating updip along the subduction fault, have been documented at both Nankai and Costa Rica (e.g., at the times indicated by the dashed lines in Figure 4).

FIGURE 7

Pressure records from Holes C0002G and 1173B (left *y* axis) and 808I (right *y* axis) showing signals associated with the 2011 Tohoku-oki earthquake approximately 800 km to the northeast (a). An expanded view of records from C0002G and C0010A is shown in (b). See Figure 2b for hole locations.

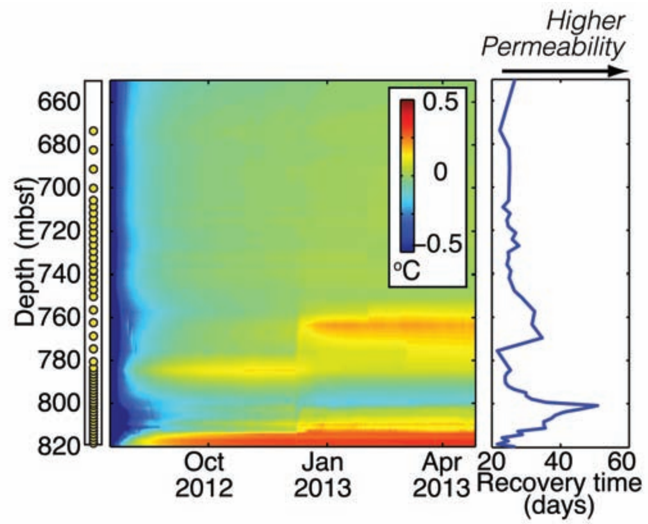


A more complete colinear transect has recently been completed with the installation of a third LTBMS in Hole C0006G at a position structurally equivalent to Hole 808I, downslope from but directly updip on the plate boundary fault from Holes C0002B and C0010A (Figure 2b; Kinoshita et al., 2018). All three are now connected to the DONET cable system and are providing data in near real time. Later in 2018, deep (>5 km) drilling efforts will begin near Hole C0002G with the goal of emplacing instruments at a location along the subduction fault where seismogenesis, not just slow slip, occurs. Once this is done, the spatial distribution of monitoring observations will be very well developed at this site, ranging from the incoming plate, across the outer reaches of the subduction zone, to the location where devastating seismic and tsunamigenic slip occurs. Results from all of these holes, as well as the array of seafloor seismometers, pressure sensors, and acoustically linked GPS benchmarks, will bring future great earthquakes into better focus and allow the associated hazards here and at other subduction zones to be more fully understood.

A final illustration of borehole observatory data comes from a hole established during the "JFAST" drilling expedition, planned and executed expressly to document the frictional behavior of the Tohoku-oki fault itself, where 2011 coseismic fault slip has been estimated at 50 m or more. Hole C0019D was drilled 16 months after the earthquake to just below the fault at 820 meters below seafloor (mbsf). A closely spaced thermistor array was installed across and above the fault and then recovered 9 months later. The data provided an unprecedented up-close view of the rupture and the formation that hosted it (Figure 8). Variations in the rate of dissipation of the thermal perturbation caused by circulation of cold seawater during drilling provided constraints on the hydrologic structure of the formation, and anomalies associated with a large aftershock showed signs of advective heat transport along a permeable horizon above the main fault zone (Fulton & Brodsky, 2016). More importantly, a 0.31°C temperature anomaly was identified at the plate fault itself, after the drilling perturbation had dissipated. This allowed an effective friction coefficient of 0.08 to be determined (a very low value) and a corresponding coseismic frictional stress of ≈0.6 MPa to be estimated (Fulton et al., 2013).

FIGURE 8

Temperature data from IODP Hole C0019D that penetrates the Japan Trench subduction thrust fault at a depth of 820 mbsf, at a location where slip on the fault during the March 2011 Tohoku-oki earthquake exceeded 50 m. The distribution of temperature sensors is shown on the left; the temperature history in the middle is shown with the background geothermal gradient removed. The hole was drilled, and monitoring began 16 months after the Tohoku-oki earthquake and ended 9 months later (Fulton et al., 2013). Time of recovery from the initial cold drilling circulation versus depth is shown on the right. Zones of higher permeability, where cold drilling water invaded the formation, are revealed by longer recovery times. Shear heating on the fault from the 2011 earthquake is reflected by elevated temperatures near the bottom of the hole. An advected thermal signal in a permeable horizon at roughly 765 mbsf began in late 2012 at the time of a local aftershock (Fulton & Brodsky, 2016).



New Sensors: Acceleration, Tilt, and Drift-Corrected Pressure

Beyond the sensors that have been successfully adapted for borehole monitoring to date are ones tested in seafloor installations but not yet employed for borehole experiments. These include newer sensors based on the quartz pressure measurement technology developed by Paroscientific Inc., with the sensing crystals loaded by masses (replacing the Bourdon tube in pressure sensors) for measuring acceleration and tilt. With characteristic full-scale ranges of 3 g and 0.1 radians, 1-ppb frequency counters provide sensitivities of 30 ng and 1 nradian, respectively. Because of the broad bandwidth of these sensors (from Nyquist frequency set by sampling period to drift-limited d.c.) and their high sensitivity and large dynamic range, they are useful for studies ranging from normal seismology and strong motion to geodesy.

An important recent development for pressure monitoring has been to sample periodically the pressure of an onboard 1-atm reference volume. This technique, known as A-0-A (Paroscientific Application Report), uses a low-drift barometric sensor to monitor the reference pressure, and a hydraulic system that operates as a three-way valve to switch the ocean pressure sensor periodically to the reference pressure and then back again. Tests have demonstrated that ocean sensor drift, commonly of the order of up to 1 kPa yr^{-1}, can be defined using this technique to a level of 10 Pa yr^{-1} (Wilcock et al., 2018). It is normal protocol during submersible visits to CORKs to check the drift of formation pressure sensors relative to the local ocean pressure by obtaining hydrostatic readings using three-way valves included in CORK wellhead plumbing. The addition of an A-0-A drift correction of the seafloor reference pressure sensor can allow correction of all long-term pressure records at the 10 Pa yr^{-1} level. In the case of the seafloor data, this provides a precision of the determination of the rate of any change of water depth of 1 mm yr^{-1}; in the case of the formation sensors, this reduces the error of observing secular strain variations arising from sensor drift to roughly 2 nanostrain yr^{-1}. These advances bring the measurement errors well below those associated with oceanographic terms that cannot be accounted for. Other methods for defining sensor drift have been developed, such as campaign visits to local reference benchmarks (e.g., Chadwick et al., 2016), but none can be done without site visits or periodic sensor recovery.

Need for Long-Term Support

The long-term monitoring experiments highlighted in this article and many more all share a need for long-term infrastructure support to allow periodic submersible or ROV site visits for data recovery and battery replacement at remote locations, to maintain cable connections to shore, and to manage the growing quantity of data acquired. In the case of autonomous instruments, improvements are needed to reduce power requirements and increase timing accuracy in order to stretch the intervals between site visits and thus reduce costs. These needs are lifted in the case of cable-connected observatories, but they share with autonomous experiments the need for funding support that stretches well beyond the normal few-year cycle for academic research grants. The justification for this is clear for many of the objectives behind the cable-connected experiments at Cascadia and Nankai described here and the autonomous installations at the Hikurangi subduction zone that are well under way (Saffer et al., 2017). Finding a long-term "home" for such observatory programs that fall somewhere between specific experiments and the type of monitoring carried out by national facilities will be critical to ensure that they last across the duration of the geodynamic cycles they are intended to illuminate.

Acknowledgments

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PAPER

Dynamic Modeling of Ship-to-Ship and Ship-to-Pier Mooring Performance

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ABSTRACT

Traditional methods for the design of ship-to-pier moorings in normal and storm conditions and for ship-to-ship moorings under normal conditions are currently based on static calculations. These calculations have served well for many years, first with natural fiber ropes and later with nylon and other low- to medium-modulus synthetics. Key to the success of this simplistic approach is lines that can elongate enough under tension to share the loads between multiple lines. When wire rope mooring lines are introduced, an increased weight catenary and the use of constant tension winches allowed enough compliance for the moorings to load share successfully.

Now, we have very lightweight, high-modulus synthetic lines like High Modulus Polyethylene (HMPE), Aramid, and Liquid Crystal Polymer (LCP), where there is almost no stretch and very little weight to form a weight catenary. When used with constant tension winches that allow the mooring load to be shared across multiple lines, these can work well. However, when they are used from bollard to chock to bit with no compliance, they are unable to share the load between multiple lines, and high tension failures occur where a weaker but more compliant mooring line would be fine.

This article describes advanced dynamic modeling of ships loaded by wind, waves, and currents in these conditions and the tension sharing between mooring lines of different materials and constructions. The need to share the mooring load between multiple lines is the crux of the issue.
Keywords: moorings, cordage, elongation

Problem Statement

A typical ship mooring to a pier or to another ship is composed of a number of breast lines that restrain motion in the transverse direction and spring lines that restrain motion in the longitudinal direction. The ship motions due to currents, winds, waves, tides, and the wakes of passing vessels result in complicated 6-D motions of translation and rotation that the mooring lines have to overcome and restrain.

Figure 1 shows a typical system of mooring lines (yellow) going from real bollard locations on an actual pier (brown) to chock and bit locations aboard a specific ship (white). There are head lines going to additional bollards on land shown in green. The arrangement shown is the aft part of a storm mooring protocol, and the forcing is varied across a tailored range of conditions shown in Table 1.

Obviously, the analysis matrix needs to build out from the limited description in Table 1. For a specific harbor, the wave direction will be limited by the opening location and the basin geometry, but a few directions may be necessary. Wind direction will need to include headings around the compass because the wind drag area is much larger in the beam direction than in the fore and aft directions. The currents should be set to match what is found locally. At the Woods Hole Oceanographic Institution (WHOI) pier in Woods Hole, MA, for instance, the 0.5- to 1.5-knots current always runs under the dock from northeast towards southwest no matter what direction the 3- to 6-foot tide is running in.

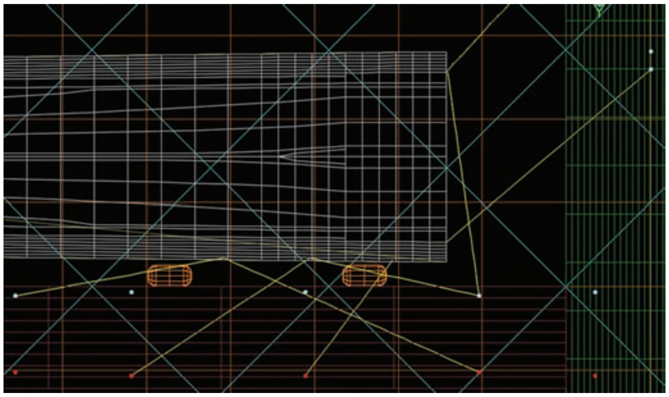
It is a fact of life that, no matter the mooring line material or the mooring arrangement, the ship will always move back and forth and side to side with pitch and roll by a small amount and the mooring lines need to be able to accommodate that small range of motion without breaking anything. The only way to completely remove these motions is to dry-dock the ship in a graving dock.

In a well-balanced mooring arrangement, each line accommodates these small motions in three ways:

- An increase or decrease in end point distance can be accommodated by more or less droop in the catenary.
- The azimuth of the line will change some, and there is very little restoring force for small changes in angle.

FIGURE 1

Stern of a typical vessel with storm moorings in OrcaFlex.



- The line will stretch like a spring to some degree. The vast differences in the tension versus elongation properties of the different ropes and how they handle these elongations is the focus of this article.

Cordage Science 101

Cordage Science is a fairly obscure discipline, and most engineers have little or no exposure to it, which has led to significant misinformation with regard to ship moorings.

Hooke's law, that is, Force = *KE*, where *K* is a spring constant and *E* is the amount of elongation, is only correct for ropes at a representational mathematics level. *K* with many cordage fibers and with different rope constructions is not a simple quantity. The spring content for mooring ropes can be time, age, loading direction, loading rate, "wet vs. dry," and tension history dependant.

Figure 2 shows the gross differences in behavior for different mooring rope materials. The figure on the left is from McKenna et al. (2004); the right-hand panel is data measured in the Buoy Lab at WHOI. The slope of a tangent fitted to these curves in the left-hand illustration is the nominal spring constant or *K* value. Note that the high-modulus synthetic lines are very similar to steel in spring constant. Polyester is in between, and nylon is the softest spring shown here. Other graphs in McKenna et al. and Himmelfarb (1957) show the Test and Evaluation (T&E) behavior of natural fiber ropes, which plot between the polyester and nylon ropes.

Figures 2 (right) and 3 both show the tension direction and time aspects of typical and textbook data from real ropes. Focusing on Figure 3 (left) from McKenna et al. (2004), we see that rope tension effects normally start at a reference tension of 200d^2, which is a tension in pounds equal to 200 times the nominal diameter in inches squared. The genesis of this odd convention is lost in antiquity. The first increase in tension and subsequent decrease do not return to zero because the fibers in the originally loose rope are pulled into alignment where they stay to some extent. This is "structural" or "permanent" elongation; however, a portion of this called recoverable may return if the rope is

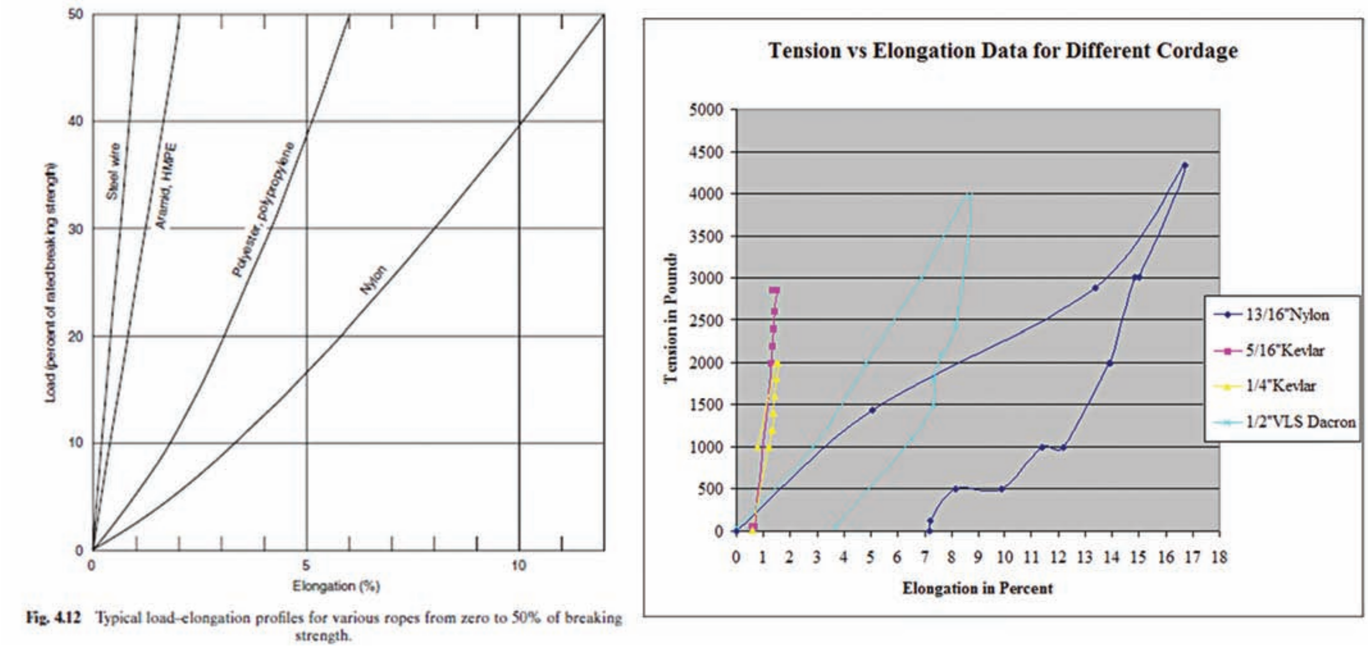
TABLE 1

Typical loading condition set.

Count	Vessel	Draft Condition	Condition Description	Wind Speed Knots	Wind Speed m/s	Current Speed Knots	Current Speed m/s	Wave Conditions H1/3 Meters	Wave Conditions Tm Seconds
1	Ship A	Fully loaded	Normal	25	12.9	1	0.51	1	7.5
2	Ship A	Fully loaded	Mild	35	18.0	1	0.51	1.25	7.7
3	Ship A	Fully loaded	Heavy weather	50	25.7	3	1.54	1.5	7.8
4	Ship A	Fully loaded	Storm	64	32.9	2	1.03	1.8	8.0
5	Ship A	Half loaded	Normal	25	12.9	1	0.51	1	7.5
6	Ship A	Half loaded	Mild	35	18.0	1	0.51	1.25	7.7
7	Ship A	Half loaded	Heavy weather	50	25.7	3	1.54	1.5	7.8
8	Ship A	Half loaded	Storm	64	32.9	2	1.03	1.8	8.0

FIGURE 2

Tension versus elongation behavior of rope materials: textbook versus sample testing.



left slack for a few minutes to hours. Turning to the Figure 3 chart on the right, again WHOI Buoy Lab data, this shows that there is a significant scatter from reel to reel. The jogs in the decreasing tension are where the tension was held constant for 10 min at each interval, but the sample length recovered somewhat over that time. Again, this shows that there is a lot of variability in the softer spring synthetics. There are many reasons for this including lay lengths, sample lengths, and so forth that are out of scope of the present article. Figure 4 shows the left panel from McKenna et al. (2004) for wet and dry nylon ropes. Of the synthetic cordage fibers, only nylon shows this much wet-dry difference.

Figure 4 (right) is from Bitting (1980) and shows that the K for dry new rope is very much different from well-worn used rope. The

FIGURE 3

Hysteresis and time effects.

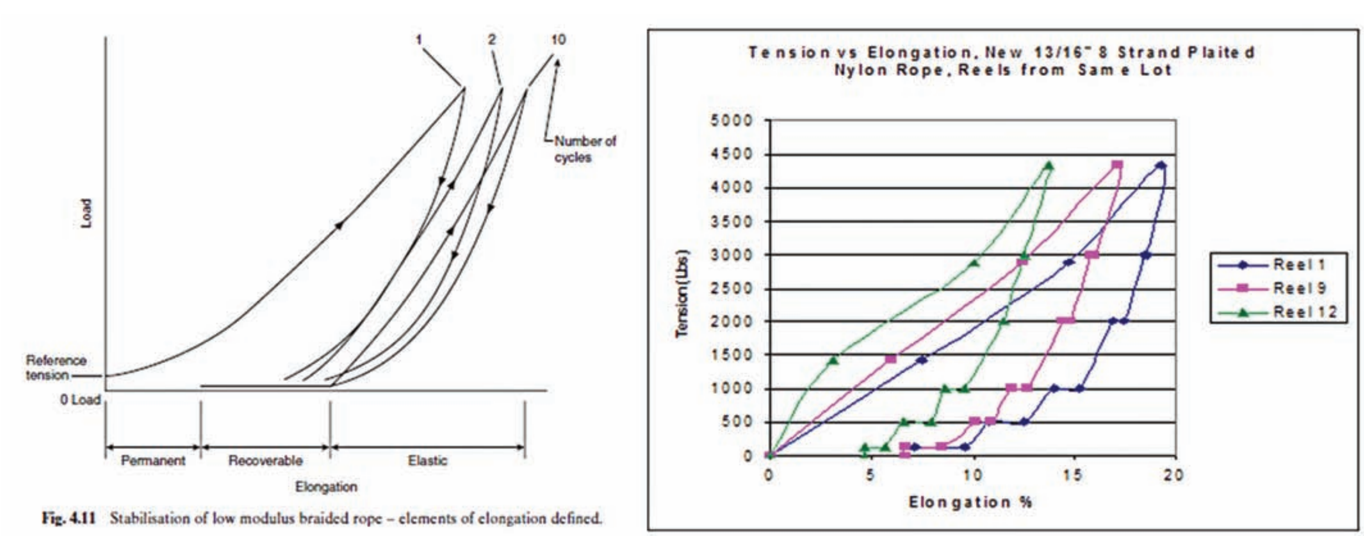
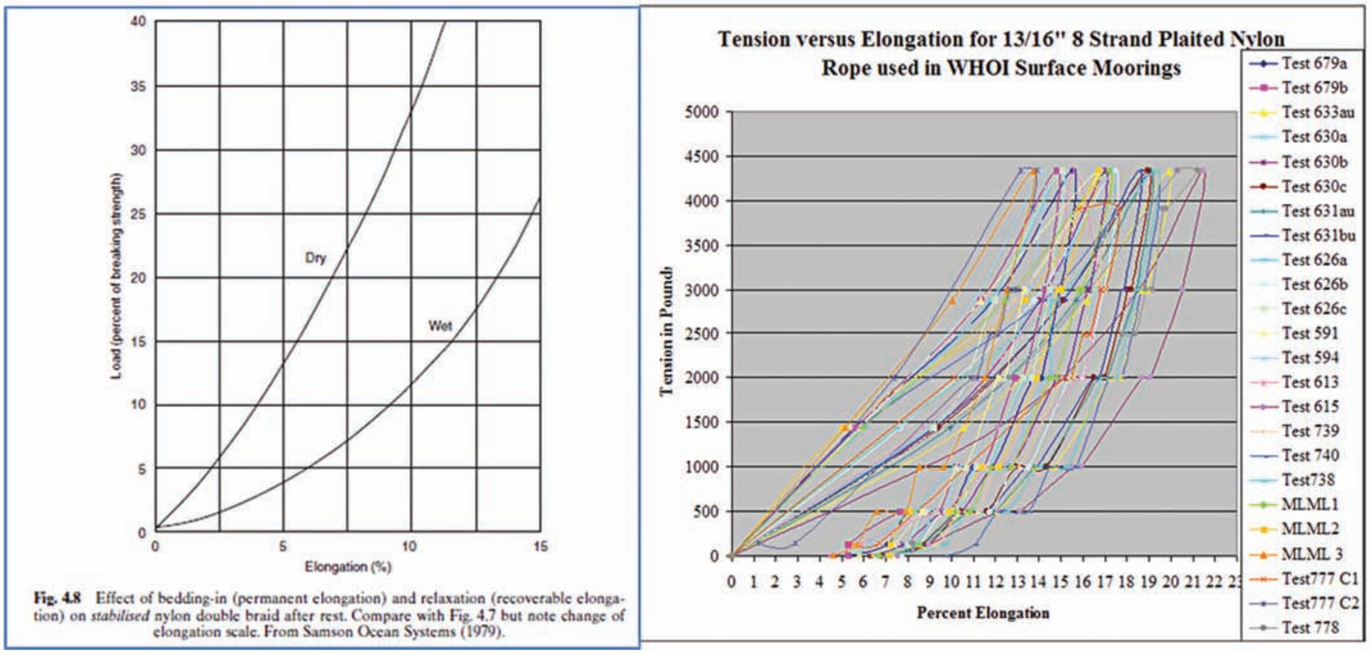


FIGURE 4

Wet and dry versus new and used ropes.



graph shown is for nylon, but the same document contains similar charts for polyester that show that the spring constant changes (softens) with age.

What Does This Mean for Ship Moorings?

When one is setting up the mooring arrangement in the real world, the crew gets a line handler on the pier to drop the end over a specific bollard. Then, they take up by hand or using a capstan or a constant tension winch to position the ship as desired. At this point, the lines are made fast on a bit or cleat with loops overlocking loops. Usually, one line is worked at a time on the forward deck and another aft. Layers are built up on the bits in some cases such that, after the last one is made up, it is impossible to adjust the length or pretension in the lower ones without unfastening the upper ones. As this has taken 10–15 min to accomplish, the ship has rolled and pitched, and drifted longitudinally and transversely a little bit. With stretchy lines and nominal wind, wave, and current forcing, this method has worked for thousands of years.

If we are making up storm moorings by adding extra lines with chafing gear where the lines pass over hard points, we wind up with more layers on each bit and even less ability to make large or subtle adjustments. That is the deck plate reality, but in engineering computational space, the technique is somewhat different.

The same basic mooring line arrangement is made up in OrcaFlex or any of several other computer programs. The author has used OrcaFlex in several different ship projects, so further discussion will speak to that experience. The exact lengths of the mooring lines are put in along with the 3-D geometry. The tension versus elongation behavior for each line or combination of lines is entered as a curve fit for each type so that the program can instantaneously determine the stretch and residual strength as accurately as the input data will support.

Then, typically, a run with steady wind and/or current and no waves is kicked off for 600 s. This only takes about 10 s of real time. Next, the mean tension in each line is entered into something like the balance sheet in Table 2. Then, the length of each line is adjusted until the tension is about the same in each breast line and the spring lines more or less match each other.

This can be automated with a python script, but the explanation is best doing it manually.

If one is attempting this setup refinement, it quickly becomes apparent that, with nylon or polyester lines, length changes of 4–6 inches are adequate to fairly quickly balance the mooring arrangement. Those

TABLE 2

Tension vs. length balance sheet.

	Pierside Line 1 Tension	Pierside Line 2 Tension	Pierside Line 3 Tension	Pierside Line 4 Tension	Pierside Line 5 Tension	Pierside Line 6 Tension	Pierside Line 7 Tension	Pierside Line 8 Tension	S2Line 7 Tension	S2Line 8 Tension
Length	34.1	17.1	21.4	16.8	19.03	16.2	26.2	20	11.98	22.38
Mean tension	2.63	1.34	0.42	0.66	0.32	0.55	0.51	0.05	2153.91	0.56
Length	33.5	16.5	20.5	16	18.2	15.4	24.8	19.2	18	22
Length										
Mean tension										
Length										
Mean tension										
Length										
Mean tension										

kind of length changes are fussy to try on deck but not impossible. From there, the runs matrix of wind, wave, and current conditions can be kicked off. The polyester or nylon lines do not maintain the perfect setup balance, but almost all of the lines stretch enough to share some of the load at any given instant in time.

Attempting that same balance procedure with high-modulus lines is much more time consuming, and length changes on the scale of a fraction of a millimeter are required to reach anything even close to a balanced arrangement. The instant and dynamic wind wave or currents are added, the high-modulus mooring arrangement goes out of balance, and typically, a single line forward and a single line aft take 100% of the load while the rest hang slack.

The character of the tension histories is very different between a typical nylon or polyester shown in Figure 5 on the left and a high-modulus line shown on the right. The softer lines show oscillations about a mean tension with a relatively low maximum in any one line because there are at least several lines sharing the load.

The tension trace in the high-modulus line on the right changes between near zero and very high impulsive spikes. Fact of life, the ship moved a few inches, and there is nothing you can do about it. The low-modulus lines stretch a little like their predecessors have for thousands of years. The high-modulus lines treat the ships' bits and chocks and the shore side bollards to what are effectively powerful high-tension hammer blows because of an abrupt impulse-like loading pattern.

The tension axes on the vertical in both cases have been redacted because it is the behavior that is of interest. A side-by-side comparison on one job with low-modulus rope showed a mean tension of a few hundred pounds, oscillations between near zero, and about 15% of the breaking strength. The same ship, mooring configuration, and conditions with the high-modulus lines produced impulsive peaks that were above 50% of the breaking strength.

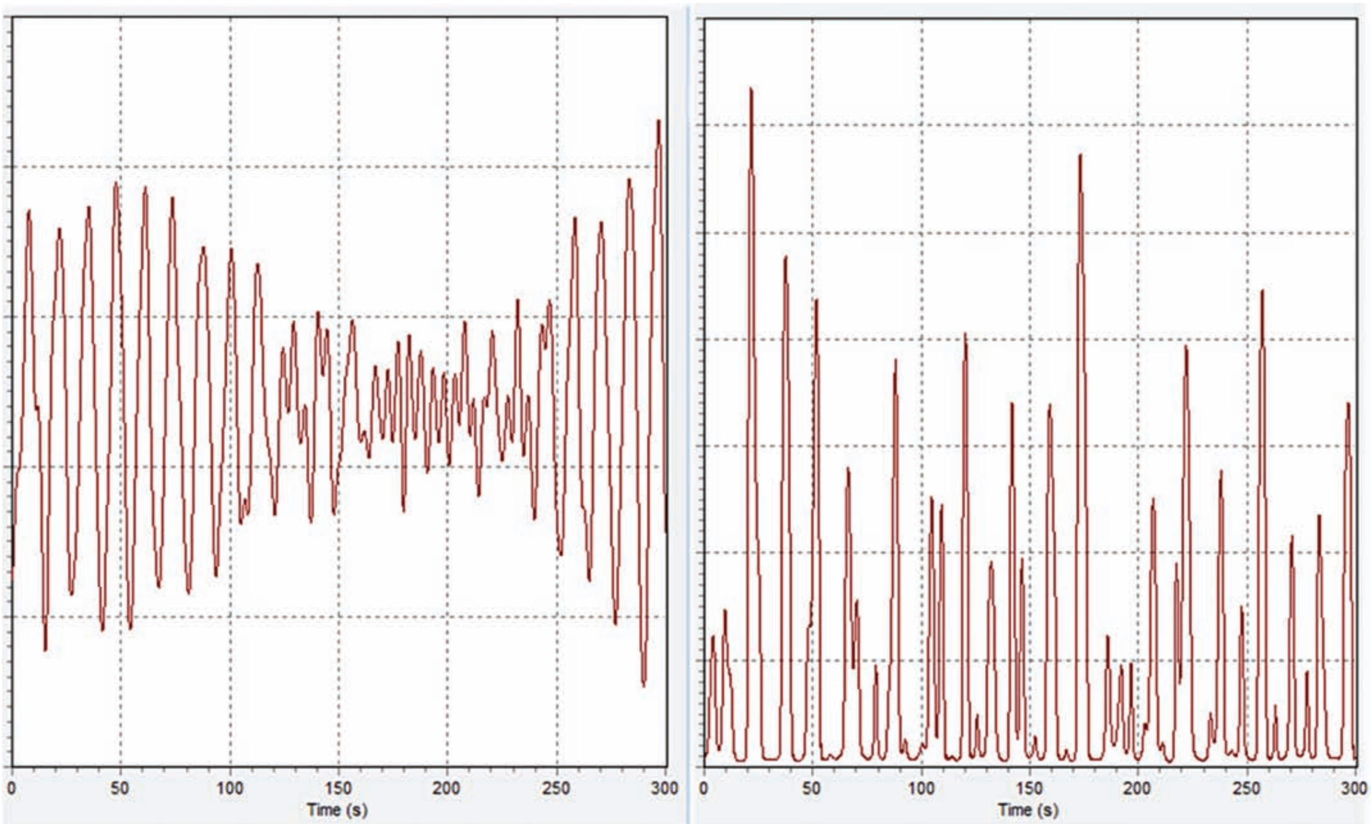
The low- to medium-modulus lines can accommodate the same small range of motions with far lower tensions, whereas they force much higher tension in the high-modulus lines. The motions will happen either way.

Closing Remarks

Like many things in the marine industry, mooring technology has evolved in many countries and on millions of ships over thousands of years. Until about the 1990s, it was not possible to calculate the behavior of a moored ship acted on by winds, waves, and currents in a dynamic

FIGURE 5

Typical line tension histories.



sense, but it almost did not matter because the tried and true stuff worked just fine.

Then, something changed that was not obvious to most users—the high-modulus synthetic ropes were invented. When they replaced steel on constant tension winches, the mariners loved them because they give a similar performance without the weight.

When used on smaller vessels that cannot afford the space or weight of constant tension winches, the problems noted herein began to emerge. These analyses were developed following a number of field failures of high-modulus lines used without compliance. It may be possible to put a 5- to 10-m length of eight-strand plaited nylon rope in series with the high-modulus lines to add compliance and get away with it. With termination effects taking several meters at each end, nylon lengths below about 5 m are not practical. One has to be very careful that the nylon link is long enough to allow up to several feet of stretch without breaking. Experience has shown that the short nylon with a longer high modulus can still be very hard to get an initial balance condition to work out. The adjustment lengths required are too small to be practically feasible.

For smaller vessels only a few hundred feet in length, there may not be any room for the added length. In that case, the mariner is advised to go with a quality braided or plaited polyester rope, which will be cheaper and much simpler to use. It is not as "high-tech," but "it works."

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COMMENTARY

MTS Buoy Technology…*"State of the Field"*

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Buoy and mooring technology dates back to the late 1950s, over 60 years ago, when Bill Richardson of the Woods Hole Oceanographic Institution (WHOI, Cape Cod, MA) wanted to measure current speed and direction at certain depths within the water column on a project that spanned the Atlantic Ocean from Cape Cod, Massachusetts to Bermuda. Using a 10-feet-diameter fiberglass doughnut (now called a toroid), a steel tower to mount an antenna, a polypropylene and nylon mooring line between the surface buoy, and a surplus anchor made from recycled railroad wheels, buoy and mooring technology was underway. Few of these initial system designs lasted longer than a month, for the high current speed of the north Atlantic Gulf Stream proved stronger than the mooring components chosen for the project. Upon Richardson's departure from WHOI, new engineering and science personnel were engaged, and the WHOI Buoy Group was formed, with the main task of addressing the series of problems encountered on those early deployments in the Atlantic. Determining component strength, longevity, what to do about "fish bite," and the big one—Piracy—were the goals. The WHOI Buoy Farm was created, and "design, deploy, and wait" became the battle cry for the group as they tested out new ideas and components for long-term deployments and collected good ocean science data sets. Similar testing of subsurface buoys and moorings was also underway during this early time frame, where flotation could be submerged below the surface, out of the line-of-fire from wind, waves, and pirates, holding up various instrumentation to sample the water column and ocean environment. These subsurface systems required the development of two new components to the field—the acoustic release and wire rope (the acoustic release for obvious reasons—the buoy and mooring needed to be detached and recovered from its anchor; the wire rope—a nonelastic (no stretch) mooring component that allowed flotation and instrumentation to be strategically positioned within the water column to make measurements at required depths). Wire rope also replaced synthetics in the upper water column where "fish bite" activity (sharks) was more frequent. Countless articles have been written and presented on this early engineering on both successes and failures in the field (the failures led to future success).

Fast forward to the 1970s—buoys and moorings had now been deployed successfully up to a year in length, and as the ocean instrumentation community also advanced, it was now possible to collect long-term *in situ* oceanographic data on a variety of projects worldwide. With strong funding support from the Office of Naval Research (ONR) and the National Science Foundation, the WHOI Buoy Group became headquarters for continued buoy and mooring systems technology development. Spin-off ideas and designs began to occur within the U.S. academic sectors and other international ocean laboratories and with the U.S. National Oceanic and Atmospheric Administration's (NOAA) Pacific Marine and Environmental Laboratory (PMEL, Seattle, WA) and the National Data Buoy Center (NDBC, Stennis Space Center, MS) finally engaged, buoy and mooring technology and its advancement were here to stay.

In the 1980s and 1990s, buoys, moorings, and components used now had a full quiver of design options for a variety of project applications. All-chain systems (shallow) in use along the coast (NOAA's National Weather Service) were and are still common. Deep water "taut line" moorings, where cutting the synthetic component (usually nylon) shorter than the site location depth uses the stretch factor (elongation) of the mooring to place and keep sensors at specific depths within the water column for critical density measurements in physical studies, have been used for decades. For long-term deployments in harsh environments (high latitudes), the "inverse catenary" (sometimes called "s-tether" moorings) has been deployed for 2, 3, and even 5 years in length and has proved very successful. These designs are now basic on many projects worldwide.

FIGURE 1

Deployment, North Pacific Ocean, 2017: Texas A&M Univ., Geochemical and Environmental Research Group (GERG), College Station, TX, and Ocean University, Qingdao, China. Photo credit: RDSEA International, Inc.

Evolving technologies in system components have given the ocean community, engineers, and scientists new means of collecting data, continuing the increased knowledge of our oceans, bays, and estuaries. Hardware components have not changed much since the 1990s. Various sizes of shackles, pear (sling) links, and chain, usually galvanized, are still necessary to make system connections, sometimes miles long in the deep ocean. The key is the proper selection of component materials (grade and strength of steel) and "isolation" (from dissimilar metals) to prevent electrolysis and minimize corrosion, the combination killer of many mooring systems over the years.

Hardware specifications are well documented; even "cycling and fatigue" points over time have been observed and published (WHOI, ONR). Miles and miles of 3 × 19 (3 strands of 19 wires each, braided together to form a rope), jacketed (polyvinyl, propylene, or ethylene) wire rope (also called Nilspin) are still the standard in the oceanographic community. Some wire ropes are torque-balanced or torque-free; this prevents rotation during deployment, another issue that can stress engineers on the back deck of research vessels. Wire rope termination points (for hardware attachments) went from poured sockets (epoxy resins) to swaged fittings hydraulically pressed onto the rope. These fittings need to be chosen for the tensions expected in the field.

Synthetics such as nylon, polypropylene, and Dacron are still the go-to components when long duration and stretch are needed in a design. When stretch is not wanted, products such as Kevlar are chosen and used with good results. Vectran, Dyneema, Spectra, and Dynex, which are relatively new to the field, are super strong and eliminate corrosion in the system. These moorings are mostly used in subsurface applications. Hydrodynamic modeling, a proven tool for the ocean engineer, has become a great asset in choosing the right buoy and mooring components.

Fast forward again to the 2000s, buoy systems are still wanted and needed, but the change in funding levels (federal, state, local, and private sector) has altered the direction of many programs and projects. A decreased use of buoy systems has occurred with supplemental employment of automated vehicles and robots, surface and subsurface now on the rise. The large basin-scaled programs such as the Global Moored Tropical Buoy Array (Atlantic, Pacific, and Indian Oceans) could scale back on surface assets and deploy FLUX sites (project backbone moorings with full sensor suites) while the ARGO Program samples water column density with profiling floats to 2,000-m depths. Surface wave gliders and sailing drones could cover the grid in between, therefore decreasing project expense while attempting to maintain good ocean science data collection.

The oil and gas (O&G) communities have scaled back as well, mostly due to market changes and shifts. As O&G moves deeper in our oceans, as expected, deep moorings with associated buoy designs will be needed to provide required information for site location environmental monitoring and studies. Measuring surface wave spectra—height, speed, direction, and frequency—will still be necessary for personnel, platform, and equipment safety. Time-series observations from the ocean's surface, throughout the water column to the seafloor using advanced measurement technology and telemetry systems often in real time, are now commonplace. Telemetry options have increased dramatically from using polar orbiting satellites—where a buoy's transmitter had to be programmed to talk to a passing satellite aloft at certain time frames throughout each day—to

FIGURE 2

Deployment, South Pacific, Equatorial region, 2017: RDSEA International and the Institute of Oceanology, Chinese Academy of Sciences (IOCAS), Qingdao, China. Photo credit: RDSEA International, Inc.

hourly, two-way communications. The Iridium Satellite Constellation, now on its second generation of satellites where no point on Earth is left untouched, has become the main frame of real-time data transfer within the community. Oceanography, meteorology, geophysics/chemistry, ocean acidification, ocean climate monitoring, ports and harbors, coastal engineering, search and rescue (USCG), and now homeland security and the Automatic Identification System all take advantage of floating surface and subsurface technology, placing data on computer servers daily at high-resolution time frames.

A viable means to keep track of this constantly evolving technology (and those engaged in maintaining and advancing it) is by the MTS Buoy Technology Committee and biannual Workshop. Initially beginning in the early 1960s as the Marine Technology Society (MTS) was being formed (bylaws, etc.), the first so-called OCEANS meeting took place in Washington, DC, with a theme focusing on "Buoy Technology." The committee formalized once Dr. Walter Paul of WHOI, with projects funded by the Ocean Engineering and Marine Systems Group of the ONR, became the Chairman. In 1996, with support from ONR and MTS, the first ONR/MTS Buoy Workshop was held in San Diego, CA, and the Buoy Workshop was on the way to becoming the mainstay for information all-things buoys, moorings, associated instrumentation, measurements, and projects. Dr. Paul has recently passed away (2017) after retirement from WHOI. His legacy in the field, system designs, the Committee, and the Buoy Workshop carry on to this day, with old school members and supporters mingling among young engineers and scientists discussing new ideas and concepts toward the same old challenges of working in our world's oceans, bays, and waterways.

Originally organized by Henri Berteaux and Robert Walden of the Woods Hole Oceanographic Institution in the 1960s, the Buoy Workshops have covered technology schemes of oceanographic monitoring, marine weather, and other parameters where floating platforms are necessary. The Workshops were initially held at random in 6- to 8-year intervals (mostly at the Capt. Kidd Tavern, in the Village of WHOI). Based on a suggestion by Dr. Tom Swean, Program Manager at ONR at the time, and with the support of both ONR and MTS and its Buoy Technology Committee, the ONR/MTS Buoy Workshop formed a more formal environment with meetings organized and supported every 2 years since 1996.

The idea was to help foster communication and exchange between engineers, scientists, technicians, operators, and end-users of buoy systems. Both the first (1996) and second Buoy Workshops (1998) were held immediately following the MTS Undersea Cables & Connectors Workshops (UC&C) and received great support from Mr. Al Berian, the long-term organizer of the UC&C annual meetings. Since 2000, the Buoy Workshop programs have included visits to facilities where active buoy work is being performed and managed. Participation ranges between 80 and 120 attendees, including many foreign participants and speakers. Thirty or more presentations are made at each 2- to 3-day workshop, leading to lively and open exchanges between the participants in this highly specialized technology. Tours of the host facility usually take place mid-week of the meeting.

Dr. Walter Paul came to WHOI with experience designing rope and hose strength members and tow cables used in towed array systems. Dan Frye, WHOI's Advanced Engineering Laboratory lead and mooring technologist, asked why we could not turn those horizontal towed hose elements vertical, increase the stretch factor, and use them as mooring riser elements. We could, and Walter did. Thus, the mooring stretch hose was

FIGURE 3

OOI cruise departure from WHOI docks, *RV Atlantis*, Pioneer array turnaround, 2015. Photo credit: RDSEA International, Inc.

born. In his years at WHOI, Walter designed mooring stretch hoses for numerous applications with varying size, strength, and elasticity. Early hoses used coil cords inside the hose to incorporate electrical conductors and, soon after, fiber optics. Walter later developed special conductor cables that could be built directly into the wall of the hose. In 2007, the call came from Chris Clark of the Cornell Bioacoustics Research Program for a means to connect WHOI's surface telemetry buoys to Cornell's passive acoustic whale monitoring hydrophones while isolating the hydrophones from surface buoy heave motions. Walter developed the lightweight and very stretchy "Whale" hose (originally called the "Gumby" hose, but Gumby was later dropped due to trademark issues) for this application—now called the Right Whale Auto-Detection or "Autobuoy" mooring. One array of 10 Autobuoy moorings off Boston and Cape Cod has been deployed year-round for over 10 years (with bi-yearly maintenance) using this technology. After working with Walter for years on cable and hose termination designs, Don Peters gradually began to assume the hose engineering "mantle." He led the development of stretch hoses used on the Ocean Observatories Initiative (OOI) Coastal Surface and Profiler moorings, pioneered the use of multiple conductor cable layers for high-conductor count hoses, and developed Ethernet-capable hose conductor cables. He has since developed a hose design for Arctic surface buoys that features high-strength, low-stretch, and high-crush resistance while carrying 12 twisted pairs for power and signals down the mooring.

Our goal here was to give a brief review of the MTS Buoy Technology Committee and the biannual Buoy Workshop. The base for this committee's efforts were housed and managed at the Woods Hole Oceanographic Institute, Cape Cod, MA, from inception (1960s), until the recent passing of the Committee's Chair, Dr. Walter Paul (2017). Many groups worldwide are involved in Buoy Technology and actively engaged in programs that employ floating, surface and subsurface buoy, and mooring systems, many of which are designed and deployed successfully due to discussions held at Buoy Workshops. We thank and appreciate all the efforts many have put into to this very eclectic group over the years, especially the work of Dr. Paul and Judy Rizoli (Workshop Administrator) of WHOI. We also thank all manufactures and vendors who have continued their participation in keeping us "a-float" (pun intended) over the decades.

Rick Cole of RDSEA International, Inc. (St. Pete Beach, FL, Co-Chair with Dr. Paul since 2004 and formerly with NOAA's PMEL and the University of South Florida's Ocean Circulation Group) and Don Peters (WHOI, Applied Ocean Physics and Engineering Laboratory) have taken the reigns of the committee and workshop, moving them into the next phase, including continued discussion on buoy and mooring technologies and their applications. We also welcome Ms. Kevyan Ann Sly, MTS Interim Executive Director, as the new Buoy Workshop Administrator. Plans are forming now for the First International MTS Buoy Workshop to be held and hosted by CSIRO in Hobart, Tasmania, Australia, April of 2019. Please see this MTS link for further information: http://www.whoi.edu/buoyworkshop/2019/

Buoy Workshop 2020 is also in discussion with information to come later in 2019.

Historical Review of Past Buoy Workshops:

1996: San Diego, CA
1998: San Diego, CA
2000: WHOI, Cape Cod, MA (Host: WHOI)
2002: Seattle, WA (Host: NOAA PMEL)
2004: St. Petersburg, FL (Host USF-Marine Science, Ocean Circulation Group)
2006: College Station, TX (Host: Texas A&M, GERG)

2008: Bay St. Louis, MS (Host: NOAA NDBC)
2010: Monterey, CA (Host: MBARI)
2012: Victoria, British Columbia, Canada (Hosts: University of Victoria, Canada IOS, and Axys)
2014: San Diego, CA (Hosts: Scripps Institute of Oceanography, OOI, and CDIP)
2016: WHOI, Cape Cod, MA (Host: WHOI)
2018: Ann Arbor, MI (Hosts: University of MI, NOAA-GLERL, CIGLR, and GLOS)
2019: In planning: 1st International MTS Buoy Workshop, Hobart, Tasmania, Australia (Host: CSIRO)
2020: In discussion, to be determined

PAPER

Maritime Renewable Energy Markets: Power From the Sea

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ABSTRACT

Marine renewable energy (MRE) is in the early stages of contributing to the energy portfolios of the United States and many other nations around the world. Although many MRE developers are designing devices that will harvest energy to contribute to the electrical grid from waves, tides, and ocean currents, a number of other promising maritime markets could be supplied with MRE power at sea. These maritime markets are often less price sensitive, have fewer options than utility-scale electricity markets, and can handle some degree of intermittency. Some of the promising maritime markets that could benefit from co-located power generation include ocean observation nodes, underwater recharge of autonomous vehicles, desalination of seawater for remote coastal areas, offshore aquaculture, shoreline protection and electricity generation, providing electricity and freshwater following coastal emergencies, providing power to islanded and isolated communities, powering and cooling nearshore underwater data centers, recharging of electric surface vessels, and personal charging of electronics. Pairing of MRE power generation with these and other maritime markets is in the early stages, but the potential for synergy and growth of MRE coupled to these markets is promising.

Keywords: marine renewable energy, maritime markets, power at sea

Introduction

Marine renewable energy (MRE)—the generation of power from the movement or constituents of seawater—is in the early stages of contributing to the energy portfolios of the United States and many other nations around the world (Ocean Energy Systems [OES], 2016). In addition to grid-scale applications, it has become apparent that MRE has the potential to add significant value when applied to established and evolving maritime sectors. Many of these applications will be small and operate off-grid; many could be used in hybrid systems with integrated storage and other renewable energy sources such as wind and solar. The ability to provide power at sea and to isolated coastal and island areas could substantially change the need for transporting and burning diesel and swapping battery banks at sea and could allow expansion of at-sea autonomous sensor deployments and other operations.

Supporting research and development of these maritime markets is an evolving focus of the U.S. Department of Energy's (2017) Water Power Technologies Office (WPTO), which is charged with a portfolio of research and development to advance innovative technologies for clean, domestic power generation from resources such as hydropower, waves, and tides. In fiscal years 2017 and 2018, the WPTO Marine and Hydrokinetic (MHK) Program has been analyzing the suitability of studying a range of maritime markets and published a report that identifies and outlines the potential opportunities and challenges for MRE in maritime markets.

MRE devices have the potential to deliver power offshore to a variety of maritime markets including powering autonomous sensor arrays, recharging autonomous vehicles, supporting aquaculture operations, and supplying desalinated water to isolated coastal regions, while providing development opportunities that are needed to advance MRE technologies. Practitioners of these maritime markets are not traditional partners of WPTO; efforts are under way to bring operators of these sectors together to better understand the potential synergies with marine renewables.

Most MRE development efforts to date have focused on harvesting power from the tides and waves as well as testing several turbines in large rivers. The first tidal turbine array was recently deployed off northern Scotland (OES, 2016). To date, most tidal, river, and wave energy deployments have consisted of one or two devices, many at small or prototype scales, tested over short windows of time (OES, 2016). Research and development efforts for harvesting power from ocean currents are under way in several parts of the world, focusing on the western boundary currents like the Gulf Stream, Kuroshio, and Agulhas (OES, 2016). Other viable MRE technologies include the generation of power from thermal gradients in tropical and subtropical waters using ocean thermal energy conversion, as well as the heating and cooling of nearshore buildings using energy generated from salinity gradients, although the deployment of these technologies has been slower than other MRE technologies (Laws & Epps, 2016; Yuce & Muratoglu, 2015). Information about the range of MRE technologies and progress in their development is documented by the 25-nation collaboration OES, convened by the International Energy Agency (OES, 2016).

Providing Power for Expanded Ocean Observations, Navigation, and Surveillance

Ocean Observations and Navigation Aids

The use of maritime sensors and navigation aids is widespread and growing rapidly worldwide. Common sensors include surface ocean observation buoys to measure meteorological data, subsurface nodes for tsunami or submarine monitoring, and surface navigation buoys for maritime traffic. Some ocean observation sensors are cabled to shore power, while others are powered locally with solar panels or batteries. As the need and capability to measure our oceans advances, more sensors that have their own unique power needs will be deployed. Battery life limits the useful duration of most observation and navigation equipment; generating renewable energy locally will enable recharging of these devices at sea (Ayers & Richter, 2016). MRE devices could provide longer-term power by taking advantage of the very environment the sensors measure, allowing for nighttime and high-latitude winter charging. Some ocean sensors are increasing in size and complexity, requiring additional power; however, quantitative estimates for the increase in power needs have yet to be estimated. Although technological advancements continue to decrease power needs for many individual sensors, there is an overall increase in the need for power for these systems (U.S. Department of Energy [DOE], 2017a) as users develop needs/requirements for more types of data and at a higher resolution to aid research and monitoring. Providing additional power at sea could also allow for larger payloads and longer deployments, while requiring minimal maintenance.

In U.S. waters, navigation aids on the surface of navigable waterways are generally managed by the U.S. Coast Guard (USCG). The range of power requirements for navigation aids, per installation, is estimated to be 10–600 kW (Brasseur et al., 2009) to support a variety of uses such as lights, air horns, radar reflectors, air and water sensors, and data transmission (USCG, 2017a, 2017b), although some simple channel markers may require much less power.

Ocean observation sites (subsurface and surface) are located along coastlines, on continental shelves, along the margin of oceanic plates, along the equator, and in other convergence zones. Monitoring systems are situated off coastlines for tsunami and storm early warning detection in the United States. Early warning systems are managed by the U.S. Integrated Ocean Observing System and the related regional system of Ocean Observing System. The Neptune array in the Pacific (Interactive Oceans, 2017), the Taos array along the equator, and the tsunami warning systems off U.S. coastlines are operated by the National Oceanic and Atmospheric Administration (NOAA, 2017a, 2017b). In Canadian waters, the Venus array operates in the Pacific waters between the United States and Canada (Ocean Works, 2017). Internationally, most observation systems are integrated with the Global Ocean Observation System (UNESCO, 2017) and the European Earth Observation System (UNESCO, 2009). Additionally, there are military and security ocean observation systems for surveillance and tracking, including systems for submarine tracking, such as the decommissioned sound surveillance system (SOSUS) array (NOAA, 2017c). Ocean observation systems are extremely varied in their power needs, and new systems are continuously being developed. Although there are no accurate estimates for system power needs across the broad array of systems, electricity is likely to be needed to power ambient monitoring sensors, communications, onboard computer systems, lighting, station-keeping (for mobile platforms), onboard maintenance (for fixed navigation and observation systems), and inspection and safety (for industrial installations at sea).

The power needs for navigation and ocean observation systems could be satisfied with MRE—generally wave power offshore, including point absorbers, oscillating water columns, and other wave devices, as well as tidal power for navigation aids in inland waters. In addition to generating electricity, compressed air could be directly generated for systems that require active ballast. Very small-scale MRE devices could be used to power isolated or drifting ocean instruments (Pinkel et al., 2011).

Recharging Autonomous Underwater Vehicles

Autonomous underwater vehicles (AUVs) and unmanned underwater vehicles (UUVs) are used for surveillance, persistent monitoring, and inspections of subsea infrastructure. These vehicles rely on surface vessels for recharging and data downloading. Their reliance on expensive and dangerous surface vessel support (a result of increased safety concerns driven by extended periods at sea for crew.) could be reduced or replaced by recharging and off-loading data underwater, thereby extending mission duration. MRE-powered recharge stations could harvest power continuously as the resource allows and—when paired with storage solutions such as battery banks—allow reliable on-demand recharging for a fleet of vehicles. Underwater recharge stations could also be used as intermediate data repositories, effectively increasing data storage capabilities.

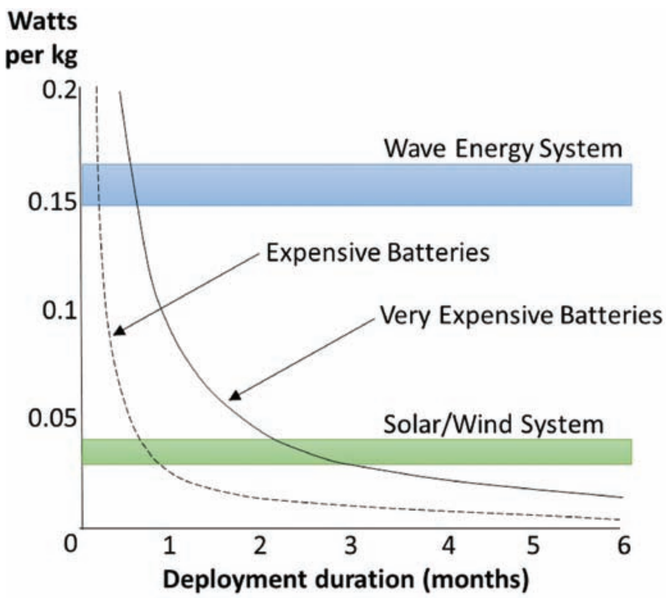
AUVs/UUVs include a range of vehicle shapes, such as torpedoes, small submersibles, and less hydrodynamic cubes used in the civilian sector for ocean observations, underwater inspections, and monitoring of the seabed and structures. In the military and security sector, they are used for surveillance, underwater monitoring, mine detection and countermeasures, payload delivery, barrier patrol, inspection, and target identification.

The resilience, surveillance, cost savings, and stealth benefits of operating thousands of small AUVs/UUVs compared to one large aircraft carrier are changing how the Navy operates and will significantly alter future at-sea operations in numerous ways (McDermott, 2017; Pomerleau, 2016; Shotts & McNamara, 1993). As modern robotics advance, AUVs/UUVs are performing maritime tasks that once took a fleet of ships months to complete. However, power remains a limiting factor; most AUVs/UUVs use onboard stored electric energy for propulsion, powering of sensors, and data acquisition. The energy storage system capacity varies with system type, but roughly 75% of the interiors of UUVs are devoted to the energy storage system (D.L. Manalang, personal communication, December 7th 2017). Deployment and recovery efforts for recharging AUVs/UUVs are time-sensitive and often limited by weather conditions, which pose a serious hazard to both the crew and the vehicle (Ewachiw, 2014; Fan & Ishibashi, 2015). MRE power at sea could provide an autonomous power source that would reduce the need to recover the vehicle as frequently and reduce the detectability of operations at sea for security and military purposes. At-sea recharging could also shorten the distance requirement for the energy storage system, enabling deployment of more, smaller, and cheaper AUV/UUVs deployed for extended mission durations (> 1 month) and/or those that consume a significant amount of power due to on-board instruments (e.g., sonar, sensors) may benefit from underwater recharging opportunities that can be powered using wave energy systems (A. Hamilton, personal communication, 7/30/2018); Hamilton (2017) estimates that wave energy systems provide a consistent form of energy that will be useful over AUV and UUV instrument deployment cycles. The power provided from wave energy systems is more consistent than that provided by battery power alone and is significantly higher than the solar/wind system, as shown in Figure 1, for a recharge station built into an observation buoy. However, battery storage may be appropriate for shorter AUV/UUV deployment durations when recharge is unnecessary.

The opportunity to recharge AUVs/UUVs underwater and to off-load payload and/or data is dependent on the availability and reliability of robust and efficient recharge technologies. Several such technologies, including physical docking stations that use wireless induction charging or plugged-in connections (Shepard News, 2015; Townsend & Shenoi, 2013), are under development by the U.S. military and its industrial partners, although none has yet reached the commercial market.

FIGURE 1

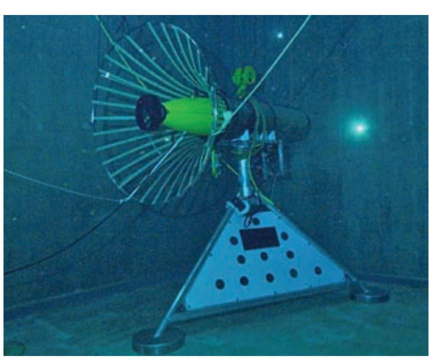
Energy requirements for deployment duration (adapted from Hamilton, 2017).



There are no commercially available docking stations for underwater vehicle recharge on the market at this time, but several research and development projects involve their use (Figure 2). Energy requirements depend on the mission requirements and the number of vehicles that will be serviced; the best estimates indicate that a typical recharging station will require between 66 kWh and 2.2 MWh (DOE 2017a). Approximately 200–500 W of charging power is required for normal charging, and typical AUV recharge takes approximately 4–8 h (A. Gish & A. Hughes, personal communication, December 7th 2017); however, faster recharge may be possible with increased power, which may be more desirable for some applications. Ideally, the recharge power source should operate over a depth range of 50–1,000 m. The constant harvest of MRE power (most likely wave power) coupled with battery backup will allow recharge on demand.

FIGURE 2

Docking station being tested in Monterey Bay Aquarium Research Institute test tank (MBARI, 2017).



Freshwater for Isolated Coastal Communities

Desalination

Seawater desalination is a small but growing part of the global water industry, with a 9% annual worldwide increase between 1990 and 2018 (Moore, 2018). In the United States, the existing seawater reverse osmosis (SWRO) market has a capacity of approximately 500,000 m^3/day (Alvarado-Revilla, 2015), primarily developed to supply municipal or domestic water use and translating to approximately \$45–\$65 million per year in electricity consumption. Currently, the desalination market is a small portion of total U.S. water consumption (DOE, 2017b), but this capacity is anticipated to grow 20% by 2020 (Global Water Intelligence, 2016). The largest customers for desalinated water are water utilities that have significant and hardened drinking water demands and long-term investment horizons, making the cost to produce water a primary driver for new technology and water supply adoption. However, there are less price-sensitive market opportunities in regions that have limited supply options, such as water-scarce locations, isolated and remote communities, disaster relief situations, and, potentially, military applications. Military environments have highly specific logistical and security concerns, for which the fully burdened cost of water can reach many multiples of the price of standard desalted municipal supply (Defense Science Board, 2016). In the near term, smaller-scale desalination systems have the potential to serve these markets, especially as SWRO and MRE technologies decrease in cost.

Desalination is an energy-intensive process, such that the cost to produce water is driven by the cost of electricity used to run the process. Other processes such as prefiltration and postfiltration require small amounts of additional energy, compared to the process of removing salt from seawater. MRE technologies can be deployed to produce drinking water with little or no electricity generation through direct pressurization of the membranes, which is advantageous in locations where grid-connected electricity is unreliable and/or costly. Although

MRE technologies can produce clean water without producing any electricity, it can be advantageous to produce some electricity to drive ancillary systems. Hybrid systems can be designed to fulfill both electricity and clean water needs of the end user. Whether a system consumes or generates electricity, or both, will depend on the economic tradeoffs and the specific market conditions in each region.

The most likely near-term deployable MRE technologies are nearshore (shallow water) wave and tidal technologies. Shallow water technologies allow for more equipment to be located onshore, require simpler installation techniques, and have lower maintenance costs, than deep water systems. However, environmental and permitting challenges associated with brine discharge and inlet designs (e.g., velocity restrictions) may incentivize deep water technologies as wave energy converter technologies mature. Nevertheless, the costs of transporting clean water to shore will have to be weighed against any potential cost reductions associated with reduced permitting restrictions.

The scalability of SWRO technologies enables MRE-powered desalination systems to appropriately match the demand scale of many potential situations. Technologies have been proposed for small isolated communities, including SAROS (https://sarosdesalination.com/) and Atmocean (https://atmocean.com/) as well as larger devices that can be integrated into larger water utility systems including Resolute Marine (http://www.resolutemarine.com/) and AquaMarine (http://www.emec.org.uk/about-us/wave-clients/aquamarine-power/). For every 1-kW average rated electrical output, approximately 8 m^3/day of freshwater would be produced; this ratio can be assumed for general scaling of wave-powered RO systems using typical recovery ratios and energy recovery systems (National Renewable Energy Laboratory [NREL], 2017).

NREL designed and modeled a system that directly pressurizes RO for clean water production, bypassing the electricity generation process, as proposed by some wave-powered desalination developers (Yu & Jenne, 2017). The results suggest that, for a standardized wave energy converter design, pressurizing an SWRO desalination system would be more cost-competitive producing water than producing electricity. Initial estimates indicate that the levelized cost of water (LCOW) is around \$1.80/m^3 (Yu & Jenne, 2017). Using an assumed electricity rate of \$0.13/kWh (California average), the levelized cost of water for a traditional SWRO desalination plant would be slightly less than \$1/m^3 (without adding distribution and other added infrastructure costs). These findings signal a near-term market opportunity for wave energy requiring smaller cost reductions before the technology becomes commercially competitive. The LCOW suggests that, when compared with existing commercial desalination technologies, wave technologies are on the order of twice as expensive, while electricity generating wave technologies are on the order of 5–10 times more expensive than average utility electricity rates in the United States (OES, 2016).

Supporting Ocean Harvests

Offshore Aquaculture

Aquaculture operations cultivate the growth of finfish, shellfish, crustaceans, and seaweeds on land or at sea, primarily for human consumption, with additional markets for animal feeds and industrial chemicals. In 2014, 73.8 million tons of fish were grown in global aquaculture operations with an estimated value of \$160.2 billion (Food and Agriculture Organization of the United Nations [FAO], 2016). China continues to be the largest producer, providing slightly less than 62% of the world fish production in the past two decades. There is an annual seafood trade gap of approximately \$14 billion per year between the United States and its trading partners (NOAA, 2015); this gap cannot be closed solely with wild caught fish and seafood. More than 90% of U.S. seafood is imported, presenting a unique opportunity for offshore and nearshore aquaculture, in addition to economic development and job creation. Aquaculture is a nascent U.S. industry; however, offshore farms are developing worldwide to meet a global market projected to be more than \$55 billion by 2020 (FAO, 2016).

Presently, marine aquaculture operational power needs include monitoring equipment, navigation lights, compressed air production, nutrient and waste disbursement, fish feeders, cold storage to refrigerate the harvested product, and crew support (lights, heat, etc.). These power needs are estimated to range anywhere from a low of 4 MWh/year for lighting to715 MWh/year for running major farm systems (Toner & Mathies, 2002), depending on the size, location, and organisms (shellfish, finfish, crustaceans, seaweeds, etc.). This power has historically been provided by diesel generation, battery bank, and, occasionally, renewables (mostly solar). By replacing fossil fuel power generation with MRE, the aquaculture industry could reduce harm to air and water quality and reduce operating costs. MRE devices may operate better on aquaculture facilities than other renewables due to their co-location characteristics, low profile, and reduced intermittency of power. Although aquaculture facilities are likely to be sited away from the most energetic wave climates, as aquaculture operations move offshore, the resulting waves will supply needed power. U.S. waters include a large (almost 10 million km^2) exclusive economic zone (NOAA, 2015), a significant portion of which could be used for aquaculture development.

In addition to growing seaweeds (macroalgae) onshore, nearshore, and at sea for human consumption, macroalgae and some microalgae can be grown at commercial scale for biofuels, animal feeds, and other coproducts. Algae have high levels of structural polysaccharides and low concentrations of lignins, making them excellent feedstocks for the production of liquid biofuels. Many algal species contain organic chemicals that are used in many industrial and agricultural processes ranging from food processing to supplementing animal feeds. Although small algal cultivation sites need little power, the larger marine farms proposed for the production of biofuels and industrial-scale chemicals and other coproducts will need energy for harvesting, drying, environmental monitoring, and maintenance activities as well as for maneuvering and buoyancy controls for larger farm structures. These power needs could be satisfied wholly or in part by energy generated from MRE devices to provide off-grid power needs by designing MRE systems into the growing and harvesting systems.

Seawater Mining

Seawater contains large amounts of minerals, dissolved gases, and specific organic molecules that can play a role as energy sources or in other industrial uses. Some of the most valuable and critically needed minerals include the 17 rare earth elements, precious metals, lithium, cobalt, and uranium. Although land-based minerals are concentrated in specific geologic formations and geographic areas, minerals in near-surface seawater are often distributed evenly in seawater, with some higher concentrations occurring near continents as a result of terrestrial runoff and interaction with margin sediments. These minerals can be recovered from seawater using adsorption methods that do not require moving vast amounts of seawater. Extracting minerals from seawater is a more environmentally friendly enterprise than terrestrial mining (Diallo et al., 2015; Parker et al., 2018). Moreover, seawater extraction will not require freshwater for processing or create volumes of contaminated water and tailings for disposal. Most rare earth elements, as well as uranium and other minerals used in the United States, are imported from other nations (Diallo et al., 2015), which raises supply chain concerns for both industry and national security (Congressional Research Services, 2017).

Wave energy could be used to power extraction of minerals or dissolved gases as this power source is locally generated, is reasonably consistent, and does not greatly add to the complexity or maintenance needs of the extraction operation. Dissolved gases like hydrogen can become important sources of energy storage and will be used in the future for maritime transportation. MRE power harvested at sea has the potential to meet seawater mining needs to power an electrolyzer for gas extraction, perform electrochemical extraction, mechanically drive an active adsorbent exposure system, and power on-site logistical needs. Ammonia and hydrogen are the most likely products that could be produced using this method (European Marine Energy Centre [EMEC], 2017).

Protecting Shorelines and Aiding Disaster Recovery

Shoreline Protection

The projected increase in extreme weather events and the threat of future sea-level rise have prompted the need for increased shore protection in the form of beach nourishment and the construction of coastal structures to reduce shoreline impacts. Integrating MRE devices with shore protection structures could be a two-pronged solution to help solve energy security and coastal protection concerns facing many coastal communities. Wave energy converters and tidal turbines can be designed and constructed into new or existing coastal structures such as breakwaters (Figure 3) and storm surge barriers (Figure 4). The lack of surface expression of these devices increases survivability and decreases visual intrusion, making them more advantageous than other renewable alternatives such as solar and wind. The energy generated by these devices can be used to power local communities, marinas and ports, or other shore protection activities, such as beach nourishment. Additionally, the sale of electricity from

FIGURE 3

Mutriku, Spain, breakwater wave energy converter integration (MarineEnergy.biz, 2016).

FIGURE 4

Five tidal turbines integrated with an Oosterscheldekering storm surge barrier in the Netherlands (HydroWorld.com, 2015).

such integrated infrastructure could defray the long-term cost of installing coastal protection.

Emergency Response

Following coastal disasters, such as hurricanes, flooding events, earthquakes, or tsunamis, there may be an immediate need for emergency power as well as safe drinking water and processed water for essential services such as heating and fire suppression systems. Isolated portions of a coastal grid may be susceptible to extended loss of power and could require a boost for grid restart—a situation referred to as a "black start." In the United States, typically the Federal Emergency Management Agency (FEMA) and/or state or community emergency services provide diesel generators for emergency power sources. As of 2014, FEMA had 1,012 generators in its fleet comprising 103 generator sizes, ranging from 1.5 kW to 1.825 MW (Danjczek, 2014), and requiring that shipments of diesel be continually delivered to disaster zones. MRE power could be used to augment or replace power from diesel generators and provide black start capability to isolated portions of the grid. All coastal areas are at risk from these natural disasters and could benefit from MRE power. Isolated grids, such as in coastal Alaska or Pacific islands, have less resiliency than areas with neighboring grid sections and could benefit the most from having an independent source of power from the sea.

Other Maritime Markets for MRE

Islanded and Isolated Communities

Hundreds of isolated coastal communities around the world have microgrid power systems from 200 kW to 5 MW in capacity; in the United States, these communities are primarily in Alaska (Alaska Energy Authority [AEA], 2017) and island territories. These communities are currently dependent on diesel generators for some or all of their power. Diesel-generated power costs are high, sometimes more than \$1/kWh, and the cost varies with the ever-fluctuating price of oil. Transporting diesel is difficult and expensive, may require extensive storage capacity, and risks contaminant spills. Wind and solar are already replacing some diesel generation but are limited in some locations by land and resource availability or the difficulty and expense of installation logistics. The U.S. Department of Defense (DOD) has dozens of permanent bases that operate in these same regions with similar electricity supply conditions as well as numerous forward-operating bases (FOBs) remote from fuel sources (Defense Science Board, 2016). For the DOD, transporting diesel fuel to FOBs and remote-operating bases takes on a significant added element of risk exposure due to the potential for loss of human life related to fuel transport. In remote communities and DOD bases, electric power is essential for lighting, heating, drinking water and wastewater treatment, and pumping water.

Most of these isolated coastal and river communities and bases have access to harvestable wave, tidal, or river current resources that could replace all or part of the diesel generation, thereby reducing energy costs and supporting the viability of the communities. Companies and organizations are developing screening approaches to identify remote communities that have high project potential for MRE development (Marine Technology Society Tech Surge, 2016).

Future Technologies: Data Centers, Electric Vessel Recharge, and Consumer Charging

Other emerging technologies may benefit from power from MRE devices as the industries develop.

Underwater Data Centers

The explosion of cloud computing and Internet-based content has created significant growth in the build-out of server centers that have very large electricity demands, a significant amount of which is needed for cooling. The energy overhead that goes to cooling accounts for one of the largest sources of auxiliary power (power not directly going to computing) and can range from 10% to 50% of total overhead depending on the facility and location but has been decreasing due to efficiencies in server and facility design, resulting in significantly improving power usage efficiencies (Rong et al., 2016; Shehabi et al., 2016; Whitney & Delforge, 2014). Customers in this market require uninterrupted power and often have 100% renewable energy targets but are very price sensitive. Companies such as Microsoft and Google have experimented with using ocean water for cooling to reduce costs. Evolving small "edge caching" data centers located near coastal population centers will require rapid paths to deployment, scalability, reduced costs, and access to renewable power. Temporary data centers for emergency and military management also require extreme ease of deployment and reliability, along with proven integration with storage and other generation sources. Future reliable low-cost MRE systems could meet this need, replacing or extending diesel supplies and operational times for these temporary centers.

Electric Vessel Recharge

Global pressures to reduce greenhouse gas emissions and improve local air quality are causing significant changes in the shipping sector (DNV-GL, 2017a, 2017b). DNV-GL reports that 185 battery-powered ships are in operation or scheduled for delivery worldwide in 2018, most in Norway and France (DNV-GL, 2017b). Additionally, fully electric passenger aircraft are presently in development, including autonomous vertical take-off or landing crafts such as "Cora" from Kitty Hawk and NASA's X-57. Similar to the charging of AUVs underwater, in the future, MRE devices could provide power to charging stations for surface vessels and aircraft, particularly in remote areas. Recharging at sea or at remote shoreside locations could extend the range and mission times of vessels, thereby broadening the type of ships and shipping activities that could use electric propulsion. This could also enable increased use of electric vessels for offshore aquaculture and for maintenance at renewable energy farms. Reducing the use of fossil fuels for powering vessels and aircraft of all sizes has the potential to mitigate greenhouse gas emissions, reduce the risk of spills at sea, and eliminate the need to transport and store petroleum products for remote locations, resulting in improved air quality, water quality, and safety at sea.

Off-Grid Small Device Charging

The rapid adoption of portable electronic devices has created a global market for charging technologies, especially in areas that have no access to grid power. At present, the two primary off-grid charging solutions are portable battery packs and small transportable solar photovoltaic panels for extended off-grid excursions. A few portable wind turbines are on the market, and water current turbines are already in use for personal watercraft applications. A small water current turbine (with a similar application for wind) is now available for personal charging. It requires that the user deploy the small device in moving water such as a stream or canal, and it charges personal devices like mobile phones by wire (https://waterlilyturbine.com/).

Summary

The MRE industry is evolving and will continue to mature and diversify over the next several decades. Maritime markets are a near-term opportunity for MRE. Maritime and grid-scale markets will feed into each other and provide learning that will increase efficiencies and reduce costs. Providing power at sea from MRE devices to serve these maritime markets will require investments by federal and state governments, as well as the private sector, to improve reliability, robustness, efficiencies, and systems integration. The co-location of an energy source at sea to supply numerous maritime sectors is a compelling reason to explore MRE as a power source. Similarly, minimal surface expressions, ease of integration with other renewable sources such as wind and solar, a low carbon footprint, and reduction in threats from fossil fuel spills and discharges all favor linking MRE with other maritime industries and uses.

Through maritime markets, MRE has the potential to make significant contributions to the future sustainable ocean economy.

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Pressure-Tolerant Electronics and Discharge Performance of Pressure-Compensated Lead Acid Batteries Under Hyperbaric Conditions

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ABSTRACT

Understanding the variations in the energy discharge performance of pressure-compensated valve-regulated lead acid (PC VRLA) batteries under the influence of increased hydrostatic pressure is essential for the reliable design of deep-ocean battery-powered systems. The paper reviews developments in the field of pressure-tolerant electronics and presents observations from the experiments done on a12 V–40 Ah absorbent glass mat type PC VRLA battery in a hyperbaric chamber at 600 bar pressure. It is identified that, during discharge at 600 bar pressure, the terminal voltage and energy discharge capacity of a 12-V fully charged battery drop by 1.05 V and about 15%, respectively, and need to be discharged below the minimum voltage levels recommended under normal ambient conditions. The identified results, along with the temperature derating factor, could be used for sizing of deep-ocean operated PC VRLA batteries.

Keywords: deep ocean, lead acid battery, hyperbaric, pressure compensation, pressure tolerant

Introduction

Oceans covering 72% of the Earth's surface house immense living and nonliving resources and play a key role in regulating the planet's climate. The technological tools used for the effective exploration and exploitation of the vast blue economic resources in the deep oceans are to be reliable, compact, and efficient (Patil et al., 2016). The weight, volume, and cost of pressure-rated metallic enclosures used for housing subsea electronics systems increases with water depth. Pressure compensation, a technique based on the principle of maintaining the system internal pressure near equal to that of the external sea water ambient hydrostatic pressure using hydraulic pressure compensating systems, helps to eliminate the need for thick-walled metal enclosures, avoid pressure-rated feed-through, and reduce thermal challenges and other associated complexities. The guidelines released by the U.S. Naval Ship Research and Development Center in the early 1970s pertaining to the design and maintenance of deep-ocean pressure-compensating systems have paved the way for developing compact subsea mechanical and electrical systems (Mehnert, 1972; Wang & Chen, 2014). Pressure-tolerant electronics (PTE) refers to the electronic components or systems developed or modified so that they can satisfactorily operate in a hyperbaric environment without the need for pressure-rated enclosures. The paper details the evolution of deep-ocean PTE systems and developments in lead acid batteries and presents observations from experiments done on a 24 V–40 Ah absorbent glass mat (AGM)-type pressure-compensated valve-regulated lead acid (PC VRLA) battery under hyperbaric conditions.

Evolution of PTE and Strategic Needs

The use of pressure-compensated lead acid batteries and propulsion system electronics in the bathyscaph *Trieste,* which descended up to an 11-km water depth in the Mariana Trench, and the development of the portable high-pressure system by the U.S. Naval Research Lab capable of characterizing the behavior of the small electronic components up to 100 MPa in 1960, marked the beginning of the PTE era (Barnes & Gennari, 1976; Sutton, 1979). Since then, constant efforts are undertaken in realizing PTE components and systems including discrete electronic components, electronic assemblies, integrated circuit chips, navigation sensors, optical devices, batteries, power capacitors, power semiconductors, and wet mate connectors. Major PTE developments reported to date are shown in Table 1.

The strategic requirements for PTE can be understood from the demand for the PC variable-frequency high-power converters and circuit breaker stations for deep-water enhanced hydrocarbon recovery systems, where significant reduction in weight, cost, and footprint could be achieved. It is reported that a 3,000-m depth-rated 15-MW-capacity medium voltage PC variable-frequency converter system could weigh only 6 t compared to its pressure-rated counterparts, which weighs about 60 t (Pittini & Hernes, 2012). It is also reported that a 6,000-m depth-rated PC enclosure of 3 m in diameter and 6 m in length used for housing multiple

TABLE 1

Major PTE developments.

Major PTE Developments Reported
Until 1970 (Sutton, 1979)
Principles of electrical wet mate connectivity demonstrated.
The U.S. Naval Research Lab (U.S. NRL) developed a 1,000-bar, 127-mm diameter, and 500-mm long pressure chamber with temperature variable between −5°C and +75°C for pressure-tolerant (PT) qualifications.
Scripps Institute of Oceanography developed PT data telemetry, compass module, and acoustic sensors suitable for operation up to 2,300 m water depth.
Scripps Institute of Oceanography developed 5.6 kW PC electric motor for use in ROV manipulators.
Digicourse developed a 6,000 m depth-rated PC compass.
1970–2000 (Sutton, 1979)
U.S. NRL conducted hyperbaric tests on different families of resistors, transistor, diodes, capacitors, and power contactors up to 700 bar hydrostatic pressure and reported that bulk carbon resistors showed a reduction in the resistances up to 30%, while film resistors were pressure tolerant.
Hybrid electro-optic wet mate connector realized in 1978 (Cairns, 1997).
2000–2010
The University of Southampton reported hyperbaric tests done on the lithium polymer cells up to 600 bar (Rutherford & Doerffel, 2005).
PC lithium ion batteries developed for Japan’s deep-water human occupied submersible Shinkai 6500 (Yoshinari, 2004).
The U.S. opto-electronics manufacturer Moog introduces commercial grade PT multiplexers and transceivers (Mackay, 2009).
Bluefin robotics (presently Mission Dynamics) developed and used PC lithium polymer batteries of 1.5 kWh capacity for the autonomous underwater vehicles (General Dynamics, n.d.).
PC VRLA battery introduced by the Deep Sea Power & Light company in the United States (Hardy et al.,2010).
Norway’s SINTEF lab analyzed the effects of the hydrostatic pressure on the capacitors used in the power conversion applications. The film capacitors were found to withstand high hydrostatic pressures (Hernes & Pittini, 2009).
After 2010
Norway’s SINTEF labs analyzed the effects of hydrostatic pressure on the power semiconductors including Insulation Gate Bipolar transistors (IGBT) and its gate driver electronics. Reported that flooding the sulfur hexafluoride (SF_6) gas-filled spaces with suitable dielectric fluid could help realize a PT IGBT (Pittini et al., 2010).
The telecom research center in Iran reported the influence of hydrostatic pressure in the performance of fiber-optic cables with varying cladding material properties (Seraji, 2012).
Norway’s SINTEF analyzed effects of hydrostatic pressure on optical components and reported that the optical components are unaffected by the short-term exposure to hydrostatic pressure (Jenkins & Thumbeck, 2008; Seraji, 2012).
The performance of the quartz-based crystal oscillator used in the ROV manipulator embedded electronics was analyzed under hydrostatic pressure. The oscillator output voltage amplitude was found to reduce up to 60% at 600 bar pressure (Kampmann et al., 2012).
Ceramic capacitors used in a power switch in the 11,000 m depth rated Deep Sea Challenger (Bingham, 2013).
A low-voltage air-break power contactor enclosed inside a dielectric oil-filled PC enclosure used for switching a 6.6 kV, 460 Hz power circuit in India’s deep-water ROV ROSUB6000 (Ramesh et al., 2013).
PC thruster motor controller of10 kW capacity used in Deep Sea Challenger (Bingham,2013).
South-West Electronic Energy (SWE) Group develops PC Li ion batteries (Adams & White, 2013).

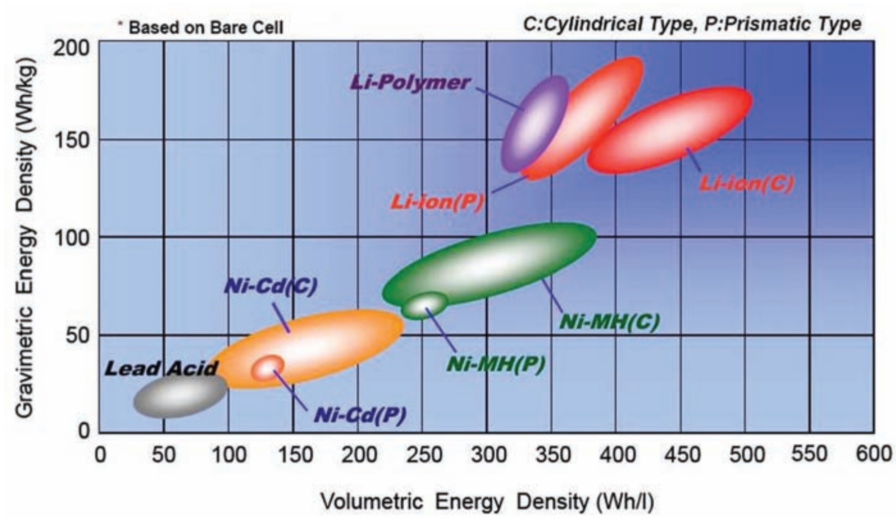
medium-voltage high-power circuit breakers could weigh about 100 t and could be eight times heavier if realized using a pressure-rated enclosure (Hazel et al., 2010). Thus, PTE is essential for overcoming the challenges associated with the design, fabrication, handling, deployment, recovery, maintenance, and logistics associated with the strategic ultra-deep offshore hydrocarbon production and remote intervention systems (Vedachalam, 2014).

Lead Acid Battery Developments

With over 150 years of proven performance in the industrial and automotive segments, the global market for the lead acid batteries was about US$35 billion in 2015 and is expected to reach $111 billion by 2025 (PRNewswire, 2017). In the offshore sector, in view of its ruggedness and reliability, valve-regulated lead acid (VRLA) batteries are used in the deep-water manned submersibles, back-up power for deep-water remotely operated vehicle (ROV) control systems, remotely operated tools, and for powering remote-located offshore oceanographic platforms (Vedachalam et al., 2014; Venkatesan et al., 2015). The performances of the LA battery along with other upcoming cell chemistries are shown in Figure 1 (Vedachalam & Ramadass, 2016).

FIGURE 1

Details of various cell chemistries (Vedachalam & Ramadass, 2016).



The LA cells (Figure 2) comprise a positive electrode composed of lead dioxide (PbO_2), a negative electrode composed of metallic lead (Pb), and a dilute solution of sulfuric acid as the electrolyte. Lead alloy grids are used to mechanically support the positive and negative active materials and also as current collectors. The grids are stacked together along with the positive and negative plates interleaved with a porous electrically insulating separator. The stacked plates are inserted into a moulded polymer case with the plates connected to the respective output terminals (Vedachalam & Ramadass, 2016).

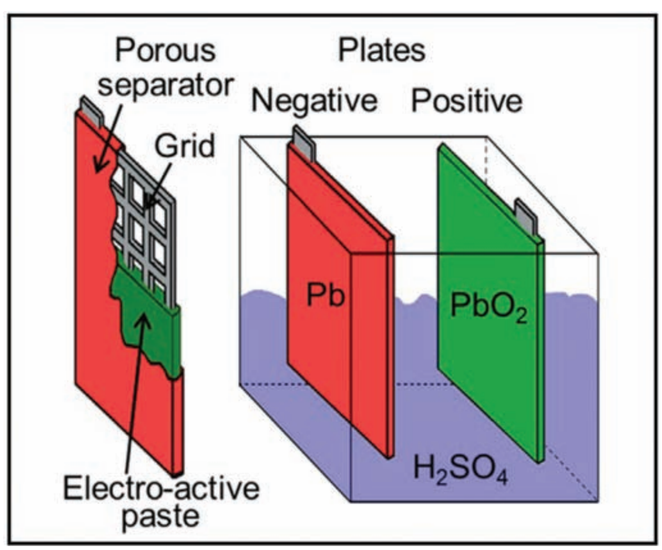
The charging and the discharge process in a lead acid battery is shown in the below reversible reaction,

$$Pb + PbO_2 + 2H_2SO_4 \longleftrightarrow 2PbSO_4 + 2H_2O \tag{1}$$

During discharge, both the electrodes are converted into lead sulfate, and the specific gravity of the electrolyte progressively reduces due the formation of water. During the charging process, reverse reactions take place. As the cell approaches full charge, the electrodes progressively get converted back to lead dioxide and lead, and the specific gravity of the electrolyte rises and reaches

FIGURE 2

Principle of a lead acid cell.



the initial concentration. Further charging leads to loss of water, as it is electrolyzed to hydrogen and oxygen. For flooded batteries, proper selection of the grid alloys and charging parameters reduces the water loss so that batteries are maintenance-free.

Increased safety and handling were achieved with the introduction of the oxygen recombination concept, meaning the oxygen and hydrogen created while charging recombine back into water inside the cell, leading to reduced maintenance VRLA cells. Another variant of the VRLA cell is the gelled cell, in which an electrolyte is mixed with a very fine silicon dioxide powder to create a gel-like paste so that the electrolyte does not spill even when the cell is inverted. Thus, the gel cells are leak proof and produce minimal off-gassing.

During early 1980, the AGM technology, which utilizes electrolyte-saturated absorbent boron silicate glass mats between the plates, was introduced. The plates and glass mats are sandwiched tightly together within a rigid frame, rendering the cells shock- and vibration-resistant and hence capable of operating even in the inverted condition.AGM batteries are capable of delivering high currents on demand and offer a relatively long service life, even when deep cycled.

During 2004, a survey conducted covering more than 0.75 million VRLA cells in the telecom, Uninterrupted Power Supplies (UPS), Photovoltaic (PV) sectors, and stationary applications covering 1.5% of the total VRLA used in the United States was conducted by the Sandia National Labs for the U.S. Department of Energy. The performance of the cells determined from the survey responses were correlated with cell design, battery configuration, and usage environment.The survey revealed that only <1.8% of the cells failed during the first 2 years of operation (De Anda et al., 2004).

Recent lead acid battery developments include carbon-enhanced designs, carbon-negative current collectors, carbon-negative electrodes, battery-super capacitor hybrids, and bipolar lead acid batteries. The use for carbon in the lead anode improves both the cell efficiency and the cycle life due to the reduced accumulation of $PbSO_4$. New formulations based on lead oxides and different conductive and nonconductive additives play a pivotal role in controlling corrosion, thereby preventing the passivation of positive electrodes in the lead acid batteries. Continuous efforts are underway in reducing cell/battery failures due to positive grid corrosion, positive grid growth, sulfation, active material softening, acid stratification, dry out, lid seal leak, vent failure, and pillar seal leaks (Enos et al., 2011; Büngeler, Cattaneo, Riegel and Sauer, 2018).

During 2009, AGM VRLA batteries were adopted for deep-ocean use by applying pressure compensation to the batteries. The PC involved filling the space above the plates and the electrolyte with adequate inert mineral oil providing compensation for the effects due to ambient pressure variations, thus eliminating the need for thick pressure-rated enclosures for housing the batteries (Vedachalam et al., 2013). However, the performance of the PC VRLA battery under higher hydrostatic pressure needs to be determined so as to apply appropriate derating factors based on the depth of operation and the ambient temperature. The discharge performance of these batteries under various temperature conditions are normally provided by the battery manufacturers. But the discharge performances of the batteries under hyperbaric conditions are not provided.

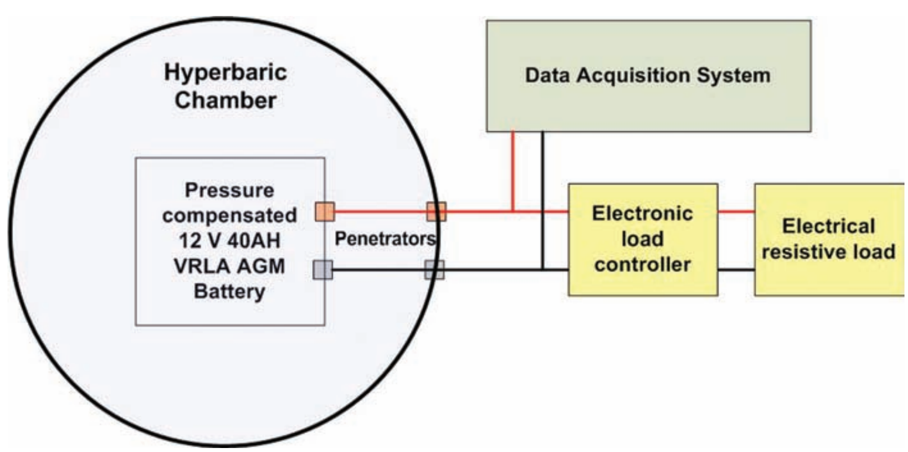
Hyperbaric Experiments: Materials and Methods

The methodology adopted for experimentally determining the influence of higher hydrostatic pressure on the performance of the PC AGM VRLA battery is shown in Figure 3.

The hyperbaric test facility at National Institute of Ocean Technology, a unique facility in Asia, is used for

FIGURE 3

Testing methodology for hyperbaric performance.



carrying out the experiments. Engineering Pressure Systems International makes a 150-mm thick walled hyperbaric chamber made of SA 723 Grade 3 Class 2 material, which has an effective internal diameter of 1 m and length of 3 m. The system produces hydrostatic pressures of up to 900 bar using water as the pressurizing medium at ambient temperature conditions (Ramesh et al., 2014; NIOT, n.d.). The system operation is controlled by a programmable control system in which the desired pressure profiles can be programmed. During the entire testing cycle, the control system continuously monitors system pressure, and when a sudden drop in pressure is experienced due to the failures or degradations in the equipment under test (EUT), the applied test pressure is released automatically. The electrical and the fiber optical feed-through provided in the chamber top flange enables online electrical and optical interface with the EUT under pressurized conditions.

The EUT comprises a Power Sonic PS-12400 model, 12 V, 40 AH AGM type VRLA battery (Power Sonic, n.d.) kept inside a dielectric oil-filled pressure-compensated metallic enclosure. Shell Diala DX transformer dielectric insulating oil is used as a pressure-compensating fluid, and pressure compensation is achieved using a rolling diaphragm-type pressure compensator. The positive and the negative terminals of the battery are connected to the external electrical loading system through the hyperbaric chamber electrical feed-through so that the batteries can be electrically loaded under pressure. The discharge characteristics of the battery under various load currents (from 0.05C to 2C) are shown in Figure 4.

The constant current loading system comprises an Agilent Technologies 6063B power electronics-controlled DC electronic loading system, which can be programmed to provide a fixed value of load current independent of the battery terminal voltage. The data acquisition system used to log the battery voltage at 10 Hz frequency comprises a National Instruments Compact Field Point (CFP) 2220 real-time controller with 16-bit ADC analog channel programmed with LabView 8.6 Version 4 software (Vedachalam et al., 2013). The data processing system is coded (Equation 2) to integrate the energy delivered by the battery with time.

$$E = I\int_0^t V\,\mathrm{d}t \tag{2}$$

The data acquisition and constant current loading systems are shown in Figure 5. Figure 6 shows the PC VRLA battery package being placed inside the hyperbaric chamber for testing under hyperbaric conditions.

FIGURE 4

Battery discharge characteristics (Powersonic, n.d.).

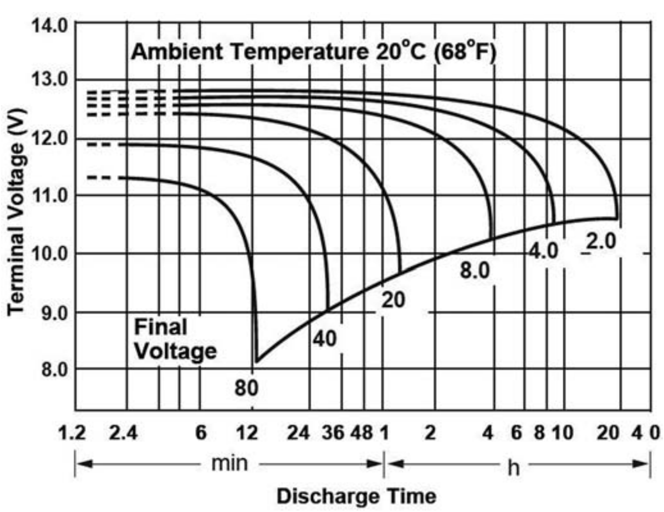


FIGURE 5

Electrical loading and data acquisition system.

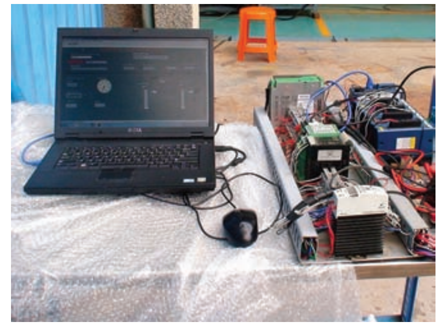


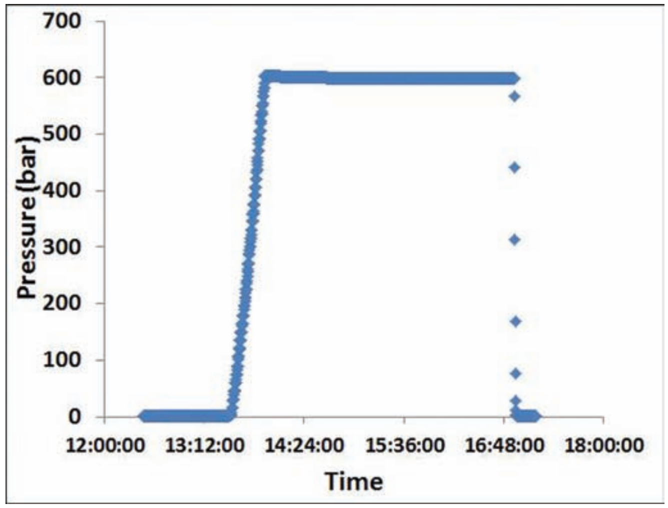
FIGURE 6

EUT placed inside the hyperbaric chamber.

The test methodology included the comparison of discharge performances (Wh) of the PC AGM VRLA battery at 0.25C under normal ambient pressure and 600 bar conditions. The experiments were carried out three times on each battery charging back after each discharge. Similar experiments were performed on three similar batteries.

FIGURE 7

EUT pressure profile recorded during the test.



Results and Discussion

Experiments were conducted for a 0.25C discharge profile under ambient conditions. Subsequently, with the EUT in place, the hyperbaric system pressure was increased at the rate of 20 bar/min and the plot of the same recorded by the control system is shown in Figure 7. Once the system pressure reached 600 bar, experiments were conducted for the same discharge profile.

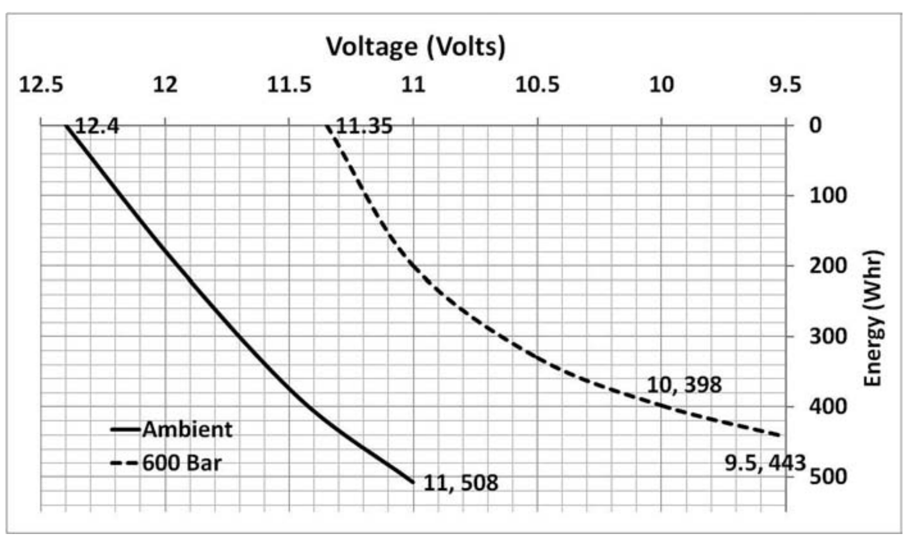
The discharge performance of the battery under both 0.25C discharge condition observed under ambient pressure and at 600 bar pressure are plotted in Figure 8. Under ambient pressure conditions, the fully charged battery with the terminal voltage of 12.5 V reduces to 11 V after delivering a cumulative energy of 508 Wh in a period of 4.07 h.

But under 600 bar pressure, for the same discharge profile, immediately on load the terminal voltage of the fully charged battery dropped to 11.35 V. Subsequently, the battery cumulatively discharged 398 and 443 Wh of energy until the terminal voltage reached 10 and 9.5 V, respectively, in 216 min (3.6 h), and thereafter, the voltage dropped rapidly. Even though the battery was drained below the recommended minimum voltage level of 10 V, the energy delivery capacity of the battery under 600 bar pressure reduced by 13% compared with the same discharge profile under normal ambient conditions. The experiments are repeated three times using the same battery, and similar experiments are done on three such batteries, and the energy delivery is found to vary in the range of 13 ± 2%. Thus, there is a reduction in the energy capacity of up to 15% and the terminal voltage by about 1.05 V for the pressure-compensated AGM-type lead acid battery when operated at 600 bar pressure. The reduction in the terminal voltage and energy capacity could be due to the probable impact of pressure on the plates reducing the active chemical area. The same could be understood in detail by carrying out microscopic studies.

The consistency in the discharge performance under hyperbaric conditions needs to be confirmed after

FIGURE 8

Discharge performance under normal and pressure.



carrying out multiple pressure cycling tests so as to ascertain the energy delivery performance under long-term usage. Furthermore, studies are being done to analyze the combined influence of low temperature and higher hydrostatic pressure, the actual scenario in the deep oceans.

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COMMENTARY

Ocean and Technology Focused STEM Education in the 21st Century: A Commentary on the Role of Professional Societies Now and in the Future

AUTHOR

Susan B. Cook
MTS Member; Marine Education, Ocean Exploration, Ocean Observing Systems Committees

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During my 35 years as an ocean scientist and educator, I have been involved in ocean-related Science Technology Engineering Mathematics (STEM) education at multiple levels. My work has included (1) precollege teacher professional development and student engagement activities at two marine laboratories, (2) service on both sides of the National Science Foundation funding desk for the Centers for Ocean Science Education Excellence (COSEE) initiative, and (3) program management at the Consortium for Ocean Leadership (COL). Since I began my work, one continuing career goal has been to foster activities that use technological tools or concepts in marine education.

In this commentary, I use degree completion data from the U.S. Departmentof Education as a proxy to examine postsecondary marine STEM education in the United States as it relates to student choices in both the ocean sciences and marine technology. Next, I identify the need for tested program design and assessment practices in precollege education, point out COSEE's legacy in this arena, and use "best practice" principles to identify four precollege programs that have been shown to be effective and have the potential to engage and prepare students for technologically focused ocean careers. Finally, I discuss how the Marine Technology Society (MTS) and other professional societies might work in partnership with marine and technology education colleagues to help expand and sustain such efforts.

Postsecondary Education: What Choices Are Students Currently Making?

Over the past 23 years, the number of students completing degrees in areas defined as marine-related programs by the federal Integrated Postsecondary Data System (IPEDS) has outpaced those completing degrees in more traditional Ocean Science CORE STEM programs. Table 1 summarizes the degree taxonomy used by IPEDS (Lettrich, 2014 and personal communication).

There has been exponential growth at the bachelor's level in completed degrees in marine-related disciplines since 1993 (Figure 1). This contrasts with the approximate doubling of total completions in the IPEDS Core STEM disciplines as listed in Table 1 over this period. By 2016, the number of bachelor's degrees awarded in the core disciplines was only a quarter of those awarded in the marine-related disciplines. The number of marine-related degrees has also outpaced graduate STEM completions at the master's and Ph.D. levels.

Within the IPEDS core marine sciences as a whole, the number of physical science and engineering degree completions has lagged behind biologically focused degrees (Figure 2). More students are completing B.S. and M.S. degrees in Marine Biology/Biological Oceanography than in Oceanography, Marine Science, and Ocean Engineering, with about three times as many degrees being awarded in the biological categories as in the physical sciences by 2016. For doctoral programs, the pattern is different with Oceanography completions consistently outnumbering biologically focused degrees since 1993.

The good news for ocean engineers and other marine technology professionals is that, although degree completions at the B.S. and Ph.D. levels have remained relatively constant, between 2006 and 2016, Ocean Engineering degree completions at the M.S. level (the standard terminal degree for the field) have increased. For example, at Florida Atlantic University, the 2016 number of 22 completions is three times greater than the six degrees awarded

TABLE 1

IPEDS classification of core and marine-related disciplines (from Lettrich, personal communication).

Core Marine Disciplines	Marine-Related Disciplines[a]
Marine Biology/Biological Oceanography[b]	Fishing and Fisheries Sciences and Management: Water, Wetlands, and Marine Resources Management; Hydrology and Water Resources Science; Wildlife, Fish and Wildlands Science and Management; Aquaculture
Oceanography—Chemical and Physical[c]	Natural Resources/Conservation, General; Natural Resources Conservation and Research, Other
Ocean Engineering	Ecology; Environmental Science; Environmental Studies; Aquatic Biology/Limnology
Marine Science (2010 to present)	Maritime Studies; Operational Oceanography; Marine Science/Merchant Marine Officer
	Geophysics and Seismology; Geochemistry; Geochemistry and Petrology; Geological and Earth Sciences/Geosciences, Other

[a]Some of these categories contain degree completions unrelated to the marine environment.
[b]Marine Biology/Biological Oceanography programs classified by their institutions as concentrations or tracks are not included.
[c]Oceanography does not include geological oceanography.

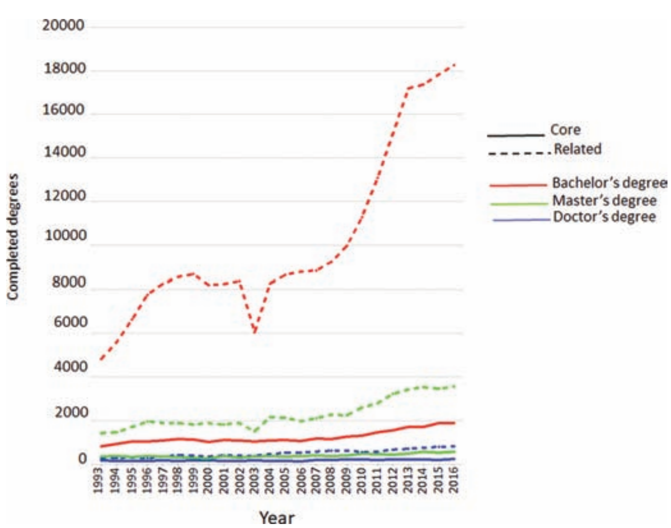
in 2006. Between 2005 and 2007, the eight top Ocean Engineering schools awarded a mean 3-year total of 18 M.S. degrees, whereas during a similar 3-year period from 2014 to 2016, these same schools awarded an average 3-year total of 59 M.S. degrees ($p < 0.001$; two-tailed t test for paired data comparisons).

Diversity remains a challenge. Although minority degree completions for IPEDS STEM Core programs have tripled at the B.S. level and increased somewhat for M.S. and Ph.D. degrees (Figure 3; Gilligan and Ebanks, 2016), levels remain well below those for Whites and foreign nationals. They are also lower than in other STEM disciplines and in the U.S. population at large (Johnson et al., 2016).

In 2016, more women earned Marine Biology/Biological Oceanography degrees than men for all three degrees (Lettrich, personal communication). Gender parity has been achieved in Oceanography and Marine Science, but not in Ocean Engineering. In Ocean Engineering, progress has been nonexistent at the M.S. level, with the percentage representation of women actually dropping slightly (21% in 2016 vs. 25% in 2007). At the doctoral level, there has been limited progress. A record number of 15 women (29% of the total) received doctorates over the 3-year period from 2014 to 2016 compared to five (17%) from 2005 to 2007, but total numbers are small and 81% of degrees are still awarded to men.

FIGURE 1

Degree completions from 1993 to 2016 from the Department of Education's Integrated Postsecondary Data System. Solid lines are core degree completions for bachelor's degrees (in red), master's degrees (in green), and Ph.D. degrees (in blue). Dotted lines depict completions in marine-related disciplines for the same three degree categories. See Table 1 for a breakdown of core and marine-related disciplines (graph updated from Lettrich, 2014, with permission of M. Lettrich).

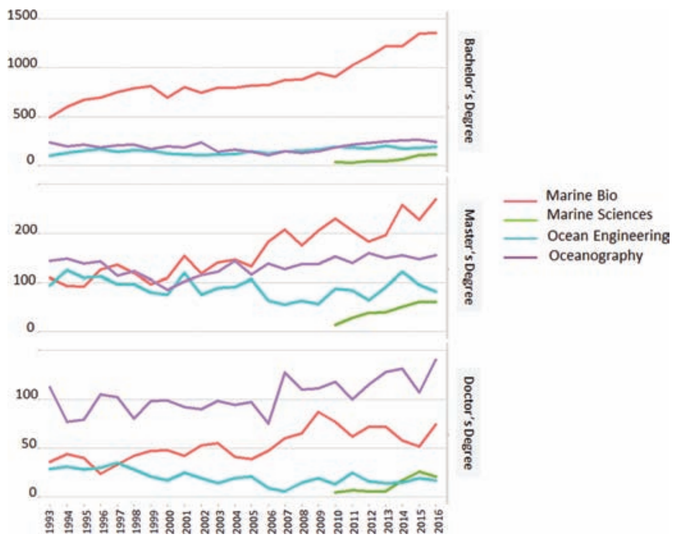


Precollege Programs: Which Technology-Focused Programs Are of High Quality and Likely To Be Successful?

For programs to successfully prepare students for collegiate and

FIGURE 2

Degree completions in four marine core disciplines from 1993 to 2016 by degree level. Data from the Department of Education's Integrated Postsecondary Data System (graph updated from Lettrich, 2014, with permission of M. Lettrich).



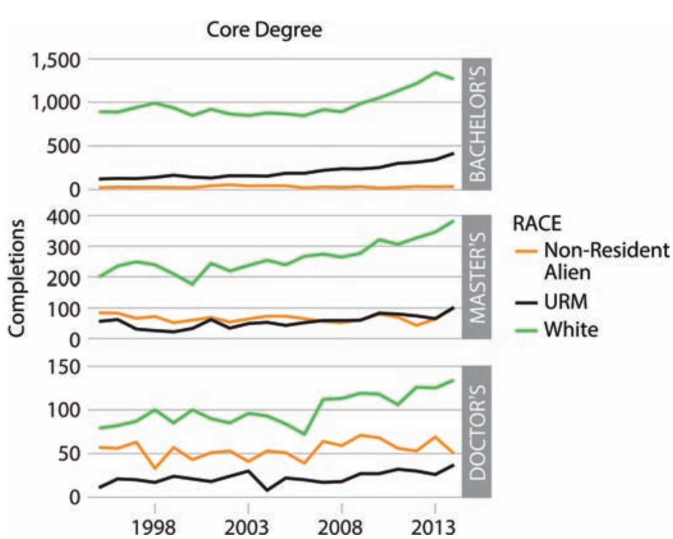
graduate work, they need to be of high quality—with design and evaluation components that meet current standards for advancing STEM learning. From 2003 to 2017, the National Science Foundation's COSEE initiative was instrumental in helping ocean scientists, educators, and technologists recognize the importance of incorporating evidence-based STEM design principles and assessment metrics into their work and building partnerships with key people and networks across the United States (Peach & Scowcroft, 2016).

Well-designed programs with the potential to be effective need to have goals that are SMART—specific, measurable, audience-based (focused on participant needs), relevant (with engaging content and realistic expectations), and time-bound (with a clear time table) coupled with detailed, well-thought-out plans to accomplish the project's goals (COSEE Networked Ocean World Broader Impacts Wizard, 2018). To make a difference nationally, programs should also have the potential to be scalable (useable in more than one institution or region), diverse (reach audiences other than Caucasian males), and sustainable (have the capacity and financial support to operate effectively). These guiding principles have been successfully applied by the technology-focused COSEE Center COSEE Technology and Engineering for Knowledge. They have also recently been affirmed and disseminated widely by the National Alliance for Broader Impacts (NABI), a National Science Foundation (NSF)-funded Research Coordination Network of university administrators and STEM professionals (NABI, 2017).

I have selected four programs as examples of high-quality marine science and technology education. These programs meet COSEE and NABI standards for design and assessment and are familiar to me through my work with MTS, COSEE, and COL. All involve "hands-on" approaches to technology education or introduce students to technological facts and concepts. They either have been scaled up to reach broader geographic areas or have the potential to be sustained and expanded to reach additional audiences.

FIGURE 3

Core marine degree completions from 1993 to 2014 by degree level for nonresident aliens, Whites, and underrepresented minority (URM) groups from the Department of Education's Integrated Postsecondary Data System. IPEDS core disciplines = ocean engineering, marine biology/biological oceanography; marine science and oceanography–chemical and physical. URM = American Indian/Alaska Native, Asian/Pacific Islander, Black/African American, Hispanic/Latino, two or more races, and unknown race (graph from Lettrich, 2014, with permission of M. Lettrich).



Marine Advanced Technology Education's International Remotely Operated Vehicle Competition

This program, coadministered by the Marine Advanced Technology Education (MATE) Center at Monterey Peninsula College and the nonprofit MATE Inspiration, has grown from a single competition in 2002 to an international juggernaut that annually engages student teams from 30 countries and 31 regions in the United States and U.S. territories (J. Zande, personal communication). At both regional and national level competitions, student teams design, build, and operate a remotely operated vehicle (ROV) within a swimming pool environment to solve real-world problems. The program's outreach to young people from elementary and middle school to high school, community college, and university allows talented students with an interest in technology to compete at levels appropriate for their age and educational level while continuing to pursue their interests and passions over time. The program also includes a significant evaluation component and is transitioning from early NSF funding to a robust and sustainable program with both in-kind and financial support from an array of technology- and community-focused businesses.

The National Ocean Sciences Bowl

Organized by the COL in Washington, DC, the National Ocean Sciences Bowl (NOSB) is a high school competition that includes both rapid fire and thought-provoking synthesis questions about ocean science facts and concepts. Student knowledge of technological concepts is tested with aspects of technology often serving as the unifying theme in annual competitions. One recent example is the 2017 theme *Blue Energy: Powering the Planet With Our Ocean*. Program evaluation including surveys of participants for over 15 years is an element that puts NOSB in a class by itself. Finding resources for tracking program participants for long enough to collect data on educational and career pathways (as NOSB does) is not a simple task.

Marine Technologies for Teachers and Students

Marine Technologies for Teachers and Students (MaTTS) represents an innovative model piloted with funding from NSF's Innovative Technology Experiences for Students program (Babb et al., 2018). Serving three New England states and run by ocean technologists and educators at the University of Connecticut, the University of Rhode Island (URI), and Eidos Education, the project introduced teams of high school students and their teachers to technologies used in ocean exploration and careers within an emerging *Blue Economy,* a futuristic term that may include technology-focused exploration and research sectors as well as more traditional ocean-focused industries such as oil and gas (Jugens, 2018). The project used multiple low-cost, build-it-yourself technologies to explore engaging biological topics (e.g., simple hydrophones to detect whale sounds, settling plates to measure changes in biological diversity, and basic sensors to monitor water quality) and introduced participants to sophisticated information and communications technologies at URI's Inner Space Center. Two key design features were the use of a 15-month suite of activities and a comprehensive evaluation protocol that identified both positive learning impacts and areas where project design and implementation could be improved.

MTS Summer Technology Camps

A fourth effort is the MTS Summer Camp program for undergraduate students with little to no knowledge or experience with marine technologies. Students learn about multiple technologies and deploy instruments as part of ongoing research and exploration projects. The week-long Marine Technology Camp at Northwestern Michigan College's Great Lakes Water Studies Institute is hands-on and gives students the opportunity to work on research vessels; use ROVs, sonar, and buoys (as well as research grade sensors) to collect data; and learn about how these technologies are applied. The week-long Marine Technology Camp at Rutgers introduces students to underwater glider robots and provides experience preparing the gliders for deployment, ballasting, navigating, piloting, and recovery. This camp is an extension of the successful Rutgers undergraduate program described in Schofield et al. (2018).

These four programs are currently at various stages of scalability and sustainability. The MATE ROV program and NOSB currently have an extensive national reach. The MTS Summer Camp initiative has expanded from one to two sites with all costs covered by student tuition MaTTS successfully completed its regional pilot phase in 2017 (I. Babb, personal communication) but currently lacks the funding to either continue as a stand-alone program or be disseminated as a tested model for others to adopt and/or adapt.

The Role of Professional Societies

So, how is all of the above information relevant? In this section, I discuss how societies might build on current knowledge about student degree completions and characteristics of high-quality precollege programs in order to strengthen and expand current programs. I focus most of my attention on MTS in part because of my earlier service as MTS Education Committee Chair. The society's distributed structure of regional and international Professional and Student Sections coupled with a Washington, DC-based headquarters is also a unique feature that gives MTS the capacity to support a broader spectrum of educational activities than other ocean-focused organizations.

At the Precollege Level

MTS and other societies should continue their intellectual and financial support for high-quality programs that meet stated goals, have potential for further expansion and sustainability, and bring both tangible and intangible benefits to the society and its membership. Over the years, MTS has stepped up to the sponsorship plate with support for the MATE ROV competition and for NOSB. Educators affiliated with MTS have played important roles in developing MaTTS and establishing the Society's Summer Camps. MTS should do whatever it can to help these exemplary programs (and others yet to be created) seek industry partners and obtain continued federal and community support.

At the Undergraduate Level

I see a larger role for the bachelor degree programs labeled by IPEDS as marine-related because many of them appear well positioned to give individuals a solid background in fundamental STEM and/or technology concepts, while at the same time introducing a larger number of students with greater diversity to applied and societally relevant issues and career pathways. One such nontraditional, innovative, and potentially valuable program is Northwestern Michigan College's new Bachelor of Sciences degree in Marine Technology (D. Sullivan, personal communication). The program emphasizes core marine science and technology concepts and combines them with technical and program management skills.

Organizations with resources that can help engage diverse undergraduate populations include the Society for Advancing Chicanos and Native Americans in Science (SACNAS) with its in-depth support structure for minority students (Garza, 2015) and the Institute for Broader Participation, which runs a web-based clearinghouse of resources for underrepresented groups.

At the Graduate Level

We need to improve our efforts to prepare more young people for emerging 21st century Blue Economy careers. To meet this challenge, Briscoe et al. (2016) have proposed a new 2 × 2 matrix model for ocean sciences graduate education. The model describes a paradigm shift in which graduate faculty and degree granting academic units work to increase the choices that students have in both coursework and research to better prepare their graduates for 21st century careers both outside academia and within it. An increased emphasis on master's level graduate training is one of the new directions that Briscoe et al. consider to be relevant, along with improved career counseling and a larger role for professional societies in providing resources to inform students about new 21st century career pathways.

The importance of such an expanded role for MTS and other societies is emphasized in the National Academies of Science and Engineering report *Graduate STEM Education in the 21st Century* (NASEM, 2018). Professional societies are recognized as an important but underutilized national resource for graduate education. The report makes the specific recommendation that societies need to play a larger role in helping "to create programs that help students make the transition into a variety of careers."

To better communicate the value of technology education to ocean science professionals, educators, and students, I encourage MTS to consider working with The Oceanography Society (TOS). TOS is a logical choice as a potential outreach partner because it is a society that represents all aspects of oceanography (biological, chemical, physical, geological) as well as education and ocean technology. A dedicated section of TOS' publication *Oceanography* highlights a broad range of ocean-focused careers, and the society is currently in the process of developing a web-based comprehensive resources page for students and early-career professionals in all aspects of ocean science.

MTS's programs for students go beyond what many societies do (see Duguay & Cook, 2016, for an overview of such ocean society programs). These include a Higher Education Guide, member-supported undergraduate and graduate level partial tuition scholarships, and an online industry mentoring program for MTS student members. Educational activities at MTS/IEEE-supported OCEANS conferences include student poster competitions, educational-focused oral presentations, and workshops for local K-12 educators.

What Else Is Needed?

I believe that it is critical for individuals with an interest in marine science and technology to be able to climb a vertical ladder of educational experiences as they move from middle to high school, into college and university level work, and finally into a 21st century Blue Economy career. For minority students in particular, such a continuum of exposure is essential because minority communities and cultures are often unaware of educational and career opportunities in marine technology and marine science (Garza, 2015). In the absence of effective outreach, traditional pathways such as medicine and the law will continue to be much more likely to attract the interest of minority students than marine-focused careers.

I consider MTS to be uniquely suited to foster such connections because of its network of regional sections serving both professionals and students interested in marine science and technology. In the past, MTS sections have been "movers and shakers"—promoting and organizing educational programs in their roles as regional hosts for MTS/IEES OES OCEANS conferences, and currently, the San Diego section is sponsoring an industry internship program. Student sections have served as valuable leadership training grounds (Sobin, 2015), have helped with recruiting for educational programs (D. Sullivan, personal communication), and could play a more active role in the future.

The SACNAS and NSF's Louis Stokes Alliances for Minority Participation (LSAMP) should be valuable partners. SACNAS' student chapters and the society's national conference provide invaluable support and career information (Garza, 2015), whereas LSAMP has worked with marine technology educators (Babb et al., 2014) in the past to successfully engage African American students.

If MTS is interested in expanding its existing programs into a larger regional and national tapestry, the Dear Colleague Letter STEM Education for the Future issued by NSF (2018) may be relevant. This DCL focuses on technology education and includes a call for Research Coordination Network proposals that could underwrite the creation of a larger network of marine education and industry partners. Such a network could, in turn, provide the intellectual capital needed to determine how best to use existing, often limited resources to tackle the challenge of engaging and supporting a larger, more diverse suite of young people from precollege through graduate school into professional technology careers.

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PAPER

MTS Manned Underwater Vehicles 2017–2018 Global Industry Overview

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ABSTRACT

The manned underwater vehicle industry continues to build momentum into 2018; much of this has been driven by strong market trends and technology. There is renewed growth in the luxury yachting industry, in citizen science, and in ocean philanthropy. Tourism submersibles offer high-end touring expeditions for boutique destinations and specialty cruise ships. In Asia, notably China, Japan, and India, deep-ocean science is gathering attention for research and commercial applications. The industry also benefits from an accepted use of lithium batteries by class societies and strong developments in the areas of navigation and communication technology. Finally, although military development typically focuses on unmanned capabilities, there is more investment in deep submergence submarine rescue vessels.

Keywords: manned submersibles, ocean research, innovation, exploration, human in-situ observation

The Marine Technology Society's manned underwater vehicles (MTS MUV) database tracks a total of 320 submersibles, of which over 160 are active around the world. This paper reviews the general classification system of MUVs with special consideration of regulations and vessels working at 300 and 1,000 m and the challenging hadal zone that reaches to depths of 7,000 m and beyond. This discussion touches on the distribution of MUVs for different market applications, international class societies, nonsubmersibles that make the news as MUVs used in the narcotics industry, and military vehicles used for submarine rescue capabilities. The last section highlights the accomplishments and challenges of active manned submersibles deployed around the world in 2017–2018.

The industry maintains an impeccable safety record, with zero recorded fatal incidents in over 40 years. A total of 122+ vehicles operate privately and commercially in tourism, research, or expedition work. Most of these submersibles are designed to international safety standards and classed by one of more than a dozen class societies that are part of IACS (International Association of Classing Societies). This dedication to safety and accepted design rules is reflected in the fact that 92% of all operating submersibles were designed, fabricated, and tested under third-party classification society review. In the context of the numerous types and differing capabilities of the growing number of submersibles, this paper will discuss improvements to bring clarity to the current regulatory systems leading to an informed public and continued safe operations.

General Review

The MUV industry continues to build momentum into 2018. The industry has been propelled by strong market trends and continues to be supported by the industry's regulatory framework, safety record, and professionalism. There is renewed growth in the luxury yachting industry, and citizen science and ocean philanthropy has been buoyed by robust stock market performances. In Asia, notably China, Japan, and India, deep-ocean science is gathering more attention for research and commercial applications. Tourism submersibles continue to offer high-end touring expeditions for boutique destinations and specialty cruise ships. Finally, although military development typically focuses on unmanned capabilities, there has been investment in deep submergence submarine rescue vessels.

The MTS MUV committee provides a forum for all in the industry who design, manufacture, and operate human-occupied vessels for extreme ocean environments. Competitive innovation, engineering advancements, and leadership contribute to the long-term business growth essential to any ocean exploration initiatives. The MUV industry is composed of 85 international member companies, including 50 MUV manufacturers of which 38 are commercial companies and 12 are state agencies. MTS MUV

TABLE 1

MTS MUV in operation in 2018 by sector of operation.

Application	No. Vehicles	%
Research	14	8.75
Tourism	36	22.5
Military/government	46	28.75
Commercial/personal	64	40.0
Total	160	

divides the industry into four major categories (research, tourism, government/military, and commercial/personal) and distinguishes three groups by depth range of operation. The depth range groups include vehicles that operate deeper than 1,000 m (Group 1), MUVs that operate from 300- to 1,000-m depth capability (Group 2), and those that operate in the range of less than 300-m range (Group 3). Table 1 shows the general distribution of MUV applications.

MTS MUV Database

The MTS MUV committee maintains a database that tracks a total of 320 submersibles, of which over 160 are active around the world, providing a capacity of 1,624 seats. This includes 38 military deep submergence vehicles used for submarine rescue/support operations. A total of 122+ vehicles operate privately and commercially in categories that include scientific research, tourism, private expeditions, commercial work, and leisure. These data do not include historical submersibles that have been inactive for more than 25 years or any personal/home-built (P/HB) submersibles because this population is too difficult to track. The best P/HB estimate in the United States would be 40–60 active vehicles and possibly an inventory of two to three times this amount as a total roster. These vehicles are designed and built by industry craftsmen with aptitude but who do not use formal design and testing documentation. It is difficult to assess the scope of such vehicles in Europe, Asia, and elsewhere, but private developments abound (W. Kohnen, 2018).

MUV Certification and Classification

The MUV industry maintains an impeccable safety record, with zero recorded fatal incidents in over 40 years. This dedication to safety and accepted design rules is reflected in the fact that 92% of all operating submersibles were designed, fabricated, and tested under third-party classification society review. Only 8% of operating vehicles are unclassed and not formally documented or reviewed by a third-party agency.

The MUV industry has evolved and grown in the past 25 years. Today it encompasses a wide range of vehicle types: Personal-amateur-built MUVs, third party-built experimental vehicles, professional-classed (IACS) submersibles, large commercial tourism subs, military vehicles, and commercial submarines. The industry is guided by an impressive set of internationally recognized safety design standards and rules: American Bureau of Shipping (ABS), Det Norske Veritas

TABLE 2

2018 MUV industry certification and classification status by IACS societies.

ABS	American Bureau Shipping	United States	33	21%
BCS	Bulgaria Class Society	Bulgaria	1	1%
BV	Bureau Veritas	France	5	3%
CCS	China Classification Society	China	4	3%
CN	China Navy	China	4	3%
DNVGL	DNVGL	Norway/DE	21	13%
IRS	Indian Register of Shipping	India	1	1%
KR	Korean Register of Shipping	Korea	0	0%
LR	Lloyd’s Register	UK	49	31%
NAVSEA	U.S. Navy	United States	3	2%
NK	Nippon Kaiji Kyokai	Japan	4	3%
RINA	Registro Italiano Navale	Italy	3	2%
RS	Russian Maritime Register of Shipping	Russia	4	3%
None	Unclassed		12	8%
OUT	Out of Class Status		16	10%
Total			**160**	

(Norway) and Germanischer Lloyd (Germany) (DNVGL), Lloyd's Register (LR), American Society of Mechanical Engineering Pressure Vessels for Human Occupancy (ASME PVHO), U.S. Coast Guard Navigation and Vessel Inspection Circular (USCG NVIC), Cayman Island Shipping Registry (CISR), and more.

Most submersibles in the MTS MUV database are designed to international safety standards and classed by one of the many class societies that are part of IACS. The main class societies for MUV rules include ABS, DNVGL, and LR. The MUVs operating per each class society are listed in Table 2. The table shows the number subs operating "in class," those operating "out of class," meaning they were designed to class but dropped out of the class survey schedule, and "unclassed" subs, including designs that were not formally documented for third-party review (Thomas, 2018; Pauli, 2018).

MUV Industry Regulations

An impressive set of internationally recognized safety standards and rules—including ABS, DNVGL, LR, ASME PVHO, USCG NVIC, and CISR—exist to provide consistency and safety to the design and construction of manned submersibles. Standards for operational procedures, however, have received less consistent attention; U.S. Coast Guard MUV operational regulations have not been reviewed since 1993. Given the small submersible technology advances and market evolution over the past 25 years, the MTS MUV community has identified a need to formulate an updated, simpler regulatory framework that can be adopted globally and will classify the many types of "Operations" according to the type of work/application performed and level of formal documentation presented to the port authorities. Proposed outlines were discussed during the 2018 MUV Symposium at Underwater Intervention, and the MTS MUV committee continues to gather inputs from industry members through 2018.

Five categories have been proposed based on the level of formal review of the design documentation. This includes a category for tourist submersibles, requiring formal classification of the design as well as flag state certification; commercial submersibles, which include classed design and preclude flag state certification if they involve six or fewer participants; experimental, unclassed submersibles, which are developed commercially but with no formal third-party design documentation review; and a personal submersible category, where the design documentation is held by an individual. Finally, the framework includes a separate category for submarines, fully self-sustaining vessels that can go out on multiday expeditions without a surface support vessel. These include very few instances today but need a separate category

TABLE 3

Proposed MUV operations consensus standard category framework.

No	Current U.S. Coast Guard Designation	MUV Proposed Revised Category	Applicability
1	SUB-Chapter T Small Passenger Vessels	Passenger tourist submersibles	Submersibles built for commercial tourism - IACS classed - Flag state certificate of inspection (COI)
2	SUB-Chapter C Uninspected Vessels	Commercial submersibles	Commercial & research submersibles - IACS classed - Flag state COI not required for MUVs of 6 persons or less
3	SUB-Chapter C Uninspected Vessels	Uninspected submersibles	Private & commercially built Submersibles - Unclassed - Experimental operation
4	Recreational Submersibles	Personal submersibles	Home built, self-operated personal subs - Unclassed - Pesrsonal noncommercial operation only
5	Submarines	Submarines	Classed submarines/work/passengers - IACS classed - Flag state COI

looking ahead. Table 3 shows a general outline of the framework in consideration (W. Kohnen, 2017).

The MTS MUV committee's long-term objective is to create a positive environment for MUV innovation, technology development, and commercial growth within the industry while guaranteeing public safety. Entrepreneurship is at the heart of all innovation, yet it is a constant challenge to balance innovation and public safety; to figure how the public, media, and regulatory agencies can readily identify between different categories of submersible operations.

Summary Review of Submersibles by Depth Classification

The MUV technologies, although similar across all types of vehicles, distinguishes three groups by depth range of operation. These general groups divide the MUVs into vehicles that operate deeper than 1,000 m (Group 1), also a benchmark commercial delimiter for vessels designed or built in the United States since vehicles with deeper capabilities are subject to U.S. export restrictions; MUVs that operate from 300- to 1,000-m depth capability (Group 2); and more versatile types of MUVs that operate in the range of less than 300 m range (Group 3).

Group 1 (>1,000 m) Hadal Depth MUVs

This group of MUVs does not receive many newcomers, but the last two additions have been from China. In 2012, China launched the *Jiaolong*. This vessel is owned by the China Ocean Mineral Resources R&D Association (COMRA) and is operated by the China State Oceanic Administration-run National Deep Sea Center. *Jiaolong* is the deepest research vehicle at 7,000-m rating. Its popularity in China created a surge of scientific interest for deep-ocean research and a backlog of dive requests because of its unique single-vehicle capability. In response, China worked on the *Deepsea Warrior*, a new 4,500-m rated research submersible, specifically designed for its national science community and released in 2017. It was built as a lighter, nimbler vehicle with an effort to maximize national content in the design and construction. It is rated to 45,00 m, an equivalent to the current state of the American *Alvin*. The China Ship Scientific Research Center (CSSRC), which designed and built both deep subs, reported a 95% "made in China" content in the new submersible.

France, Japan, and the United States maintain their existing state-owned deep submergence vehicles. Woods Hole Oceanographic Institution (WHOI) announced that *Alvin* is scheduled to complete its Phase 2 overhaul to gain its full depth capacity of 6,500 m by 2020. Two other deep submersibles were added to the database for Russia, although the subs are not new. These are *Rus* and *Consul*, which have been appearing notably in public articles. These AS37 type are Russian versions of the *Mir* submersibles. The two *Mir*s are still at the PP Shirshov Institute in Moscow but are laid up and not operational (Sagalevich, 2018). The two AS37 vehicles are primarily operated by the Russian Navy. Since the twin *Mir* submersibles are within reasonable range (technically and economically) to be put back in operation, Russia holds a unique deep-ocean MUV force (Table 4).

The race for full ocean depth (FOD) capability has abated among philanthropic organizations since James Cameron's deep dive in 2012. The *Deepsea Challenger* is not likely to return to operation, but China and Japan are hard at work to conquer the deep ocean. Rainbowfish, based out of Shanghai Ocean University, continues its private development of the three-person FOD manned vehicle. In February 2018, CSSRC also announced that the national shipyard was initiating the design and construction of an FOD manned submersible, as well as an unmanned vehicle to reach 11,000 m. Japan has no immediate plans for the development of an 11,000-m submersible but is working to reestablish its FOD access with a new remotely operated vehicle (ROV) system to replace the capability from the unfortunate loss of its 11,000-m flagship ROV *Kaiko*.

In South Korea, Korea Research Institute of Ships and Ocean Engineering (KRISO), a state technology and development agency, has expressed interest in the development of a deep manned submersible, capable of 6,000-m depth. KRISO was established in 1973 with a focus on ship and ocean engineering to develop and commercialize new, original technology. Although its primary field is deep-sea robotics, it maintains an interest in developing MUV capability, pending government support (KRISO, 2017).

In India, the National Institute of Ocean Technology (NIOT), based in Chennai, is concentrating efforts on developing its own national 6,000-m rated manned submersible, the *Matsya 6000*. Researchers at NIOT have been working for many years, and most of its work has been focused on deployment and operation of a 6,000-m deep ROV system. This has proven valuable training and learning for the agency, which is still working to conclude its contract for the development of its manned vehicle, after several false starts. Still, the

TABLE 4

Group 1 "hadal depth" submersibles in 2018.

Country	Name	Depth (m)	No. Pax	Operator	Year Built	Class	Manufacturer
China	*Jiaolong*	7,000	3	China NDSC/COMRA	2009	CC	China Ship Scientific Research Center
Japan	*Shinkai 6500*	6,500	3	JAMSTEC	1989	NK	Mitsubishi Heavy Industry
France	*Nautile*	6,000	3	Ifremer	1985	BV	Ifremer
Russia	*Rus AS-37*	6,000	3	Russian Navy	2001	Russia Navy	Malakhit Design Bureau/Admiralty Yard
Russia	*Consul AS-37*	6,000	3	Russian Navy	2009	Russia Navy	Malakhit Design Bureau/Admiralty Yard
Russia	*Mir 1**	6,000	3	PP Shirshov Institute of Oceanology	1987	DNV GL	Rauma-Repola Oy
Russia	*Mir 2**	6,000	3	PP Shirshov Institute of Oceanology	1987	DNV GL	Rauma-Repola Oy
China	*Deepsea Warrior*	4,500	3	China Academie Sciences	2017	CCS	China Ship Scientific Research Center
United States	*Alvin*	4,450	3	Woods Hole Oceanographic Institute	1964	NavSea	Woods Hole Oceanographic Institute
United States	*Pisces V*	2,000	3	HURL, Hawaii Undersea Research	1973	ABS	Hyco
United States	*Pisces IV*	2,000	3	HURL, Hawaii Undersea Research	1971	ABS	Hyco

Indian Research Center is committed to move forward and bring India into the community of countries with deep-ocean research capabilities, motivated by deep-sea exploration for resources such as polymetallic manganese nodules, methane hydrates, hydrothermal sulfides, and cobalt crusts spread over the 1,000-m to 5,500-m water depth in the Indian Ocean.

Group 2 (300–1,000 m) Ocean Exploration MUVs

A report by the Rodriguez Group stated that the growth of the global yachting industry in 2017 was near 20% and that this market growth appears to be sustained for 2018. It noted that the average size of large yachts has grown from 47.8 m in 2013 to 51.6 m in 2017. This has a direct impact on the market for specialized MUV designs that consider the specific needs of large yacht operations, both for accommodating special owner requests as well as the all-important launch-and-recovery logistics. Table 5 shows the deliveries of yachts over the past 5 years. Although the yachts get larger, the space allocated to MUV storage and staging is all critical, and many of the manufacturers have tuned designs specifically for this market.

In 2017, a total of 102 MUVs operate in the Group 2 "deep-ocean" vehicle range from 300 to 1,000 m. Table 6

TABLE 5

Yachts in production and deliveries 2013–2017 (Rodriguez Consulting, 2018).

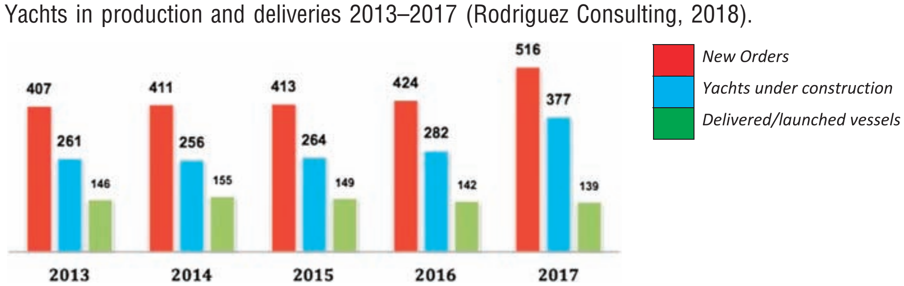
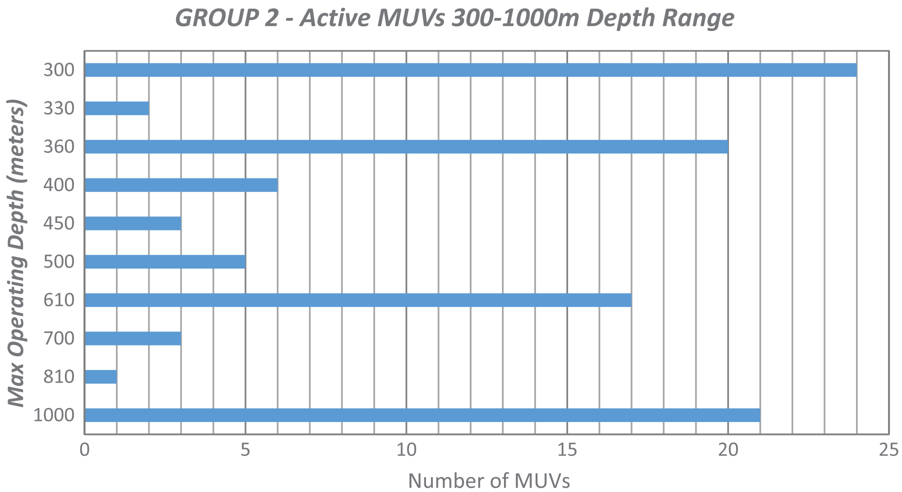


TABLE 6

Depth capacity of Group 2 "deep-ocean" submersibles in 2018.



shows the distribution of the number of vehicles for the different depth rating of the vehicles. This group is primarily driven by private and commercial operations, including filming, philanthropic research, and private leisure operations. However, most of the vehicles in the 360-m range represent atmospheric dive suit (ADS) systems used by navies around the world. It is noteworthy that this list includes more than 37 new MUVs delivered in the past 5 years, with an average depth capability of 660 m.

Group 3 (<300 m) Coastal Ocean MUVs

There are 49 MUVs operating in coastal ocean waters in less than 300 m. These include many large tourist submersibles, which generally operate between 30- and 40-m depth. This also includes small private submersibles designed for leisure, commercial work, and some research vehicles. The tourism sector is very active, consisting of large 40+ passenger submersibles made by Atlantis Submarines in Canada and produced by Mobimar in Finland, accounting for 22 of the 49 vehicles. Both companies continue to safely and successfully operate a fleet of submersibles around the world. These have toured millions of tourists in the waters from the Mediterranean to the Atlantic, Caribbean to Hawaii, and the Pacific coastlines of Asia. These vehicles are all highly regulated by both class societies and flag state authorities to ensure passenger safety. However, few new large submersibles are being produced due to mature development of commercially viable locations and the lack of new viable sites. This is an opportunity for any vehicles that can exploit smaller niche markets and novel designs when depth requirements for safety margins are reduced. A new series of tourism operations is planned by a joint venture between DeepFlight and Rainbowfish Ocean Technology. Their composite technology models will be launched with LR classification, offering a sufficient but reduced depth rating of 40 m for touring expectations and receiving certification for their new materials technology implementation. Although nonmetallic pressure hulls are not new, they remain on the fringe of class society approval due to challenges in verification and inspection of finished items. Creating mechanisms of approval for new materials is also a rich field for innovation and regulatory expansion.

A few other submersibles with diver lockout capability fall in this group, naturally restricted by diving limits. Although it has elicited interest from private users, it has been of primary interest by navies for diver delivery capability. Several new submersibles are in construction for the U.S. Navy as diver delivery vehicles, which were designed and developed through a combination of commercial classification and naval rules to streamline cost of production. M-Subs in the United Kingdom, Lockheed Martin in Florida, together with DNVGL in Germany and NAVSEA found new synergies between commercial and naval regulations in the development of the new S351 seal delivery vehicles (see Submergence Group). This process worked less well for the Navy's DCS-Light concept.

Deep Submergence Rescue Vehicles

MTS MUV tracks government and military submersible activities, primarily submarine rescue capabilities and technologies. Unmanned capabilities are increasing in scope, but manned submersibles remain at the heart of submarine rescue operations worldwide. The majority operate as independent submersibles, capable of docking with a distressed submarine and taking on 12–24 crew members to surface. There are currently 18 deep submergence rescue vehicles (DSRVs) serving various international navies. The U.S. Navy operates the PRM1 *Falcon* system as part of the Submarine Rescue Diving and Recompression System(SRDRS). It consists of a tethered manned vehicle that interfaces with a surface rescue system installed on a Vessel of Opportunity (VOO) enabling transfer under pressure (TUP) from the rescue vehicle to the decompression compartment. The rescue system is maintained and operated by Phoenix International, based in San Diego, California, which is scheduled to test the complete SRDRS system for the first time, including the pressurized rescue module (PRM), TUP, and decompression chambers in 2018. Japan, Italy, and Russia have developed their own systems and designs. For its part, James Fisher Defence (JFD) has delivered several new rescue vehicles for countries around the world based on its LR5 technology, with its latest model delivered to India last year. China has developed its own submarine rescue vehicles since the 1970s and launched its 7103DSRVs in 1987. Upgraded in

TABLE 7

Deep submergence rescue vehicles in 2018.

No	Country	DSRV Name	Depth (m)	No. Pax	Operator	Year Built	Class	Manufacturer
1	Australia	*LR5* DSRV	400	16	Australia Navy	2005	LR	James Fisher Defence
2	China	*LR7* DSRV	300	18	China Navy	2008	LR	Perry Slingsby
3	China	*Type 7103 DSRV 1a*	360	22	China Navy	1987	China Navy	Wuchang Shipbuilding Factory
4	China	*Type 7103 DSRV 1b*	360	22	China Navy	1987	China Navy	Wuchang Shipbuilding Factory
5	China	*Type 7103 DSRV 2a*	360	22	China Navy	1987	China Navy	Wuchang Shipbuilding Factory
6	China	*Type 7103 DSRV 2b*	360	22	China Navy	1987	China Navy	Wuchang Shipbuilding Factory
7	India	*DSRV-INDIA*	600+	16	India Navy	2017	LR	James Fisher Defence
8	Italy	*SRV-300*	300	12	Italian Navy	1999	RINA	Drass-Galeazzi
9	Japan	*JMSDF DSRV 3*	700	12	Japan Ministry of Defense	2017	NK	Kawasaki Heavy Ind
10	Japan	*JMSDF DSRV 2*	700	12	Japan Ministry of Defense	2002	NK	Mitsuboshi Heavy Industry
11	Japan	*JMSDF DSRV 1*	700	12	Japan Ministry of Defense	1985	NK	Kawasaki Heavy Ind
12	Korea	*LR5K DSRV-1*	400	16	Republic of Korea Navy	1995	LR	James Fisher Defence
13	Korea	*DSAR-5* (*DSRV-11*)	500	16	Republic of Korea Navy	2009	LR	James Fisher Defence
14	Russia	*AS-34* DSRV	1,000	25	Russian Navy	1989	Russia Navy	Project 1855–PRIZ Class
15	Russia	*AS-28* DSRV	100	25	Russian Navy	1986	Russia Navy	Project 1855–PRIZ Class
16	Singapore	*DSAR-6*	500	16	Republic of Singapore Navy	2010	LR	James Fisher Defence
17	Sweden	*URF* DSRV	450	16	Sweden Navy	2012	LR	James Fisher Defence
18	United Kingdom	*NATO DSRV NSRS*	610	16	British Royal Navy	2008	LR	James Fisher Defence
19	United States	PRM 1 *Falcon*	610	16	Phoenix International for U.S. Navy	2009	NAVSEA	Oceanworks International

1996, the 7103DSRV was never able to dock with submarines tilted at larger angles and limited to 1.5-kt currents. In 2008, China imported the *LR7* DSRV, built by Perry Slingsby in the United Kingdom, rated to 300 m. The Chinese Navy deployed the *LR7* during the joint RIMPAC exercises with the U.S. Navy in Hawaii in 2016 and completed exercises with the Russian Navy in 2017. Table 7 shows the DSRV vehicles by country along with general capacity information and year of launch.

2017 also saw a major submarine accident with the disappearance of the Argentine submarine *ARA San Juan* in November 2017. The tragic loss of the submarine with the death of 44 crew members renewed international focus on the limited resources available to support submarine rescue around the world's oceans. The *ARA San Juan* was an older type TR-1700-class diesel-electric submarine built in Germany, launched in 1985 and subsequently upgraded from 2008 to 2013. The search for the submarine and crew mobilized ships and aircraft from 18 nations before being called off on November 30, when it was concluded that there was no hope of survivors. The search continued through December using unmanned vehicles to find the wreck. The fate of *ARA San Juan* remains a mystery and has not been found (Figure 1).

FIGURE 1

ARA San Juan submarine, Argentina Navy.

Narco-subs

A category of submersible that is not included in the MTS MUV database is that of narco-subs: subsurface vehicles that are often coined as submersibles but are semisubmersible vehicles that operate near surface with long-range combustion engine power. Used to traffic narcotics for over 25 years, these vehicles receive media coverage when there is dramatic news about seizures and scuttling of vehicles. Figure 2 illustrates the scale of the sea travel problem. This is the 2016 recorded level of traffic between South and Central America for "noncommercial" maritime events, traveling from Colombia and Ecuador to Mexico and Guatemala. The U.S. Coast Guard reported that almost 455,000 pounds of cocaine and heroin, worth $6 billion, was intercepted in 2017, which exceeded the 2016 record. Nearly 600 suspected smugglers were apprehended by the Coast Guard, up from 465 in 2016 and 373 in 2015. Of course, most of these events do not involve narco-subs, but it illustrates the context in which their development grows in sophistication.

UC3 Nautilus

In August 2017, *UC3 Nautilus,* a "home-made" submarine, sank off Denmark, in what was revealed to be a grisly crime; the owner-builder of the submarine had deliberately scuttled the vessel after murdering a young reporter onboard. In addition to the horror at the loss of life, the MUV community recognized the potential for damage to the reputation of the submersible community as seen by regulators, insurance companies, individuals, and the media. During the investigation, it was widely reported that the submarine was not certified and even that the owner had "talked about wanting 'to be free from authorities' in making his submarines" (Jeong 2018).

FIGURE 2

2016 Noncommercial maritime events from Colombia and Ecuador to Guatemala and Mexico (Woody, 2017).

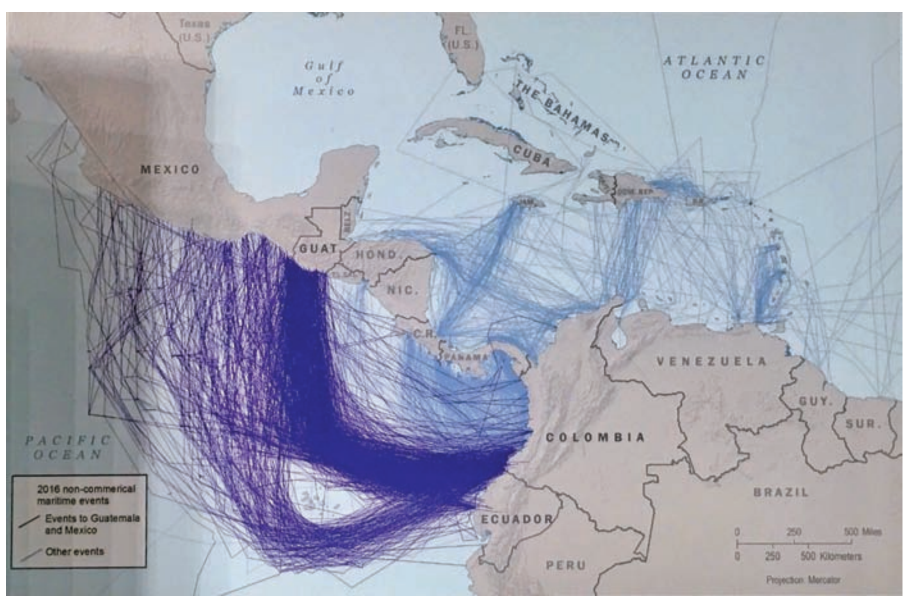


FIGURE 3

UC3 Nautilus home-made submarine.

Although this distanced the incident from the MUV submersible industry, the event highlighted the importance of awareness of public, media, and regulatory agencies of the differences between amateur, uncertified craft and those that have been properly certified. The MUV operations consensus standard is an important tool to address this issue (Figure 3).

2018 Manned Overview (Alphabetically by Company)

The following section reviews a series of submersibles that were active in 2017–2018 and provided an activity report to the MUV committee. Although this is not meant as a complete review of all vehicles, it illustrates the wide variety and differing capabilities and purposes of today's state of submersible technology and operations. The submersibles are listed alphabetically by the simplest operation designator, either a manufacturer, an operator, or a research vessel.

Alucia M/V (WHOI)

The *Alucia* is a private research and exploration vessel, 56-m long, with a versatile launch and recovery platform for a wide range of diving and submersible operations. It is equipped with the latest in technical diving, filming, and scientific research equipment and contains two subs—*Nadir* (Triton 3300/3) and *Deep Rover 2*—both of which are rated for a maximum depth of 1,000 m. *Alucia* conducted 12 missions in 2017 and spent over 200 days at sea with ports of call in Antarctica, Uruguay, Brazil, Cuba, and the United States. The Submersible Operations Group completed 84 dives with *Deep Rover* and 98 dives with *Nadir* carrying out outreach and scientific objectives. Highlights include dives in Wilhelmina Bay and St. Peter and St. Paul Archipelago. The program is commissioning a new support vessel in 2019, which will be fitted with a man-rated A-frame launch and recovery system (Tarantino 2018) (Figure 4).

FIGURE 4

M/V *Alucia* with *Nadir* and *Deep Rover*.

Aquatica Submarines, Canada

Aquatica Submarines is a Canadian-based submersible manufacturer that provides design, manufacturing, sales, and operations of manned submersibles. The company's *Stingray 500* is a light displacement three-person, acrylic hull, classed by DNVGL and rated to 500-foot depth. Throughout 2017, Aquatica's team of pilots operated the submersible in the coastal waters for Vancouver, Canada, to conduct a range of dives and expeditions. Dive missions included tourism operations with Tier 1 tour providers, scientific research and biological monitoring of artificial reefs, commercial surveys, and several film and media expeditions. The company provided dives and lectures for the TED 2017 Convention in the waters off Vancouver, Canada. It also used its submersible to film a subsea commercial featuring 360° technology with Samsung products, scheduled to air in early 2018, and was featured on the Discovery Channel's "Daily Planet and Tech Week."

Aquatica's *Stingray 500* was used to conduct a series of dives for Canadian research organizations, including the Underwater Council of British Columbia, the Artificial Reef Society of British Columbia, the Marine Life Sanctuaries Society, and the Vancouver Aquarium. One of the expeditions resulted in the discovery of a large glass sponge reef previously unknown to scientists and was featured on Discovery Channel. The glass sponge discovery renewed interest from conservation groups and the public. In response, Aquatica developed a 360° virtual reality experience to facilitate education and stewardship to be made available through social media outlets for National Geographic. Aquatica's regular diving schedule also focused on sixgill sharks in Canadian coastal waters and continues to work closely with scientists to film and showcase this species.

The company has signed new contracts for the design and manufacture of a series of underwater vehicles that to include the standard 500-foot-rated model and add a new 1,000-foot (305) model. In addition to the deeper submersible design, Aquatica also plans to launch a new line of transport vehicles designed to reduce costs associated with submersible operations, transport, and delivery. The company is scheduled to launch the

FIGURE 5

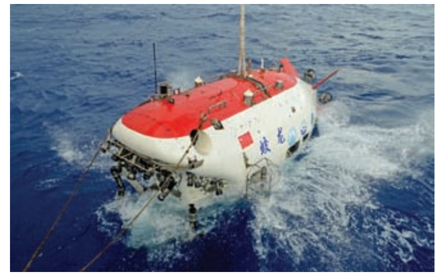
Aquatica *Stingray 500*.

FIGURE 6

Bulgaria Academy of Sciences *PC8B* submersible.

FIGURE 7

Jiaolong deep-sea submersible.



new vehicles in 2018 (Flemming 2018) (Figure 5).

Bulgaria Academy of Sciences, Bulgaria

PC8B is a three-person, 250-m-rated Perry submersible, launched in 1971 and operated by the Institute of Oceanology, Bulgarian Academy of Sciences (IO-BAS), located in Varna, Bulgaria. IO-BAS is a national research center using the submersible for interdisciplinary monitoring of the Bulgarian part of the Black Sea basin.

Dr. Ilko Shtirkov reported that in 2017 the director of the institute, who strongly supported the underwater activities, passed away. The new director, faced with budget shortages, cut all planned expeditions and is working on the refit of their support ship *Academic* to renew its 5-year class certificate from Bulgarian Register of Shipping. It is expected to take a year to organize the refit.

The submersible obtained its 5-year class renewal but performed only a single dive in 2017 to take a water sample from the geothermal spring, which was discovered at 140-m depth several years ago. Researchers were surprised that the spring had stopped its activity, possibly due to several earthquakes that took place in the region. The institute is challenged to find a new pilot to continue the subsea research as government budgets for science have been severely cut for 2017 and 2018, and most expeditions operate in joint projects funded by the European Union (I. Shtirkov, 2018, personal communication) (Figure 6).

China National Deep Sea Center, P.R. China

China National Deep Sea Center (NDSC) is based in Qingdao and is the home of *Jiaolong*, China's 7000-m-rated deep-ocean research submersible. *Jiaolong* is owned by the COMRA, and the NDSC research center is operated by the China State Oceanic Administration. *Jiaolong* is a three-person submersible designed and built by the CSSRC and classed to the China Classification Society (CCS). Named after a mythical dragon, *Jiaolong* is China's first manned deep-sea research submersible, developed by Chinese designers starting in 2002. During a test dive in June 2012, *Jiaolong* reached its deepest depth—7,062 m—in the Mariana Trench. Since January 2013, the submersible has made a total of 152 dives (Figure 7).

The submersible's mother ship, *Xiangyanghong 09*, returned to the National Deep-Sea Base in Qingdao in June 2017, ending the 38th oceanic expedition and the submersible's 5-year trial phase. During the 138-day expedition that started on February 6, *Jiaolong* and its mothership sailed nearly 34,000 km into the South China Sea, northwestern Indian, and northwestern Pacific oceans. *Jiaolong* conducted 30 dives for scientific investigations and to collect samples. Researchers from the State Oceanic Administration, Ministry of Education, Chinese Academy of Sciences and China Geological Survey dove with the *Jiaolong* to collect 625 kg of seabed rocks, 5,968 L of seawater, as well as 2,115 marine creatures. During the expedition, the submersible made five dives in the Mariana Trench and the Yap Trench, both in the western Pacific Ocean. These dives were organized for scientists to better understand the trenches' geochemical and biological conditions.

After the mission, *Jiaolong* is scheduled for a yearlong overhaul and technical upgrades. The submersible is planned to start its formal operation phase in 2018, designed take the submersible farther away on expeditions (Ye, 2018),

CSSRC, P.R. China

CSSRC is China's largest ship and ocean engineering research institute with 500+ research engineers for the research of ship design and high performance underwater engineering.

FIGURE 8

Deepsea Warrior—4,500-m research submersible.

CSSRC has worked on the development of submersible technology since 2002 when it started the design of the 7000-m-rated *Jiaolong* submersible. It was developed with a combination of national and international technology and completed its certification in 2012 to become the deepest operating research submersible today. Afterwards, in 2015–2016, CSSRC developed and launched two new acrylic-hulled tourist submersibles, the *Huan Dao Jiao Long 1* and *2*, rated to 40 m for seven passengers plus two crew, for commercial operation on Hainan Island. The focus of its progression aims at developing an increased national capability of submersible technology (Figures 8 and 9).

In 2017, CSSRC completed China's newest manned submersible, named *Shenhai Yongshi* or *Deepsea Warrior*. It was officially delivered to the Academy of Sciences in November 2017, designated to serve China's dynamic marine scientific research programs for the next 30 years. The new submersible is a three-person vehicle rated to a depth of 4,500 m. Among its major features is the fact that it is 95% national technology content. Major domestic components include the personnel sphere, underwater acoustic communication system, and acoustic Doppler velocity log instruments. The *Deepsea Warrior* has been eagerly awaited by scientists in China to increase deep-ocean access capacity. The completion of this submersible also helped expand the technology foundation for the next vehicle. CSSRC announced that its next project will be the development of an FOD manned submersible. The FOD vehicle is currently under construction at the shipyard in Wuxi, near Shanghai. The plan also includes the parallel development of a new unmanned vehicle capable of FOD. China's Haidou 1 unmanned vehicle helped set a hadal technology foundation when it dove to a depth of 10,767 m near the Mariana Trench in 2016. During the trip, the autonomous underwater vehicle (AUV) made two dives to 9,000 m and twice to 10,000 m. This made China the third country after Japan and the United States to have reached deeper than 10,000 m. Both vehicles are scheduled for completion by 2020 (Ye, 2018).

FIGURE 9

Huan Dao Jiao Long tourism submersible.

China DSRV, P.R. China

China's development of DSRVs started in 1971 at the Wuhan Shipbuilding Factory with the design of the *Type 7103* vehicles. Construction of *Type 7103* DSRV begun in 1976 and was launched for initial sea trials on January 1980. Engineering developments and tests continued through when final tests were conducted for deep diving, wet and dry rescues. The design included a crew of four with the capacity for 22 sailors. The vehicle weighed 32 tons and was rated for a maximum rescue depth of 300 m, later overhauled to 360 m. The power system was based on silver zinc batteries. The *Type 7103* DSRV was formally handed to People's Liberation Army Navy (PLAN) on November 1987. A total of four *Type 7103* DSRVs were built, with two vehicles in operation at any given time. The DSRVs are supported by *Type 925 Dajiang* class ASR/ARS ship that can carry two DSRVs during rescue missions. The *Type 7103* was overhauled in 1996 to improve its positioning system, introduce new electronics, and increase its rescue depth rating to 360 m.

In 2008, the PLAN imported the *LR7* DSRV. It was put in service in 2009 and was intended to modernize the navy's submarine rescue capability from its 1970s-based technology of the *Typ3 7130* DSRVs. *LR7* was constructed by the British firm Perry Slingsby System, a development of the earlier LR5 submersible. The *LR7* is 25-foot long, capable of rescuing 18 sailors per trip and rated to a depth of 300 m. The battery charge allows for 12 h of operation before recharging (Figure 10).

FIGURE 10

China *LR7* rescue submersible.

The Chinese navy (PLAN) participated for the first time alongside the navies of 25 countries, including the U.S. Navy, in July 2016 during the RIMPAC submarine rescue exercise off Hawaii. The *LR7* was deployed from the mothership *Changdao*, and it docked with a simulated underwater submarine wreck. This was a milestone in Sino-American naval relations. In 2017, *LR7* participated in the "Joint-Sea 2017" Sino-Russian exercise that took place in the Sea of Okhotsk in September 2017. The exercise conducted the first underwater mating of the *LR7* rescue vehicle with a Russian submarine simulating a disabled boat on the sea bed (Tate, 2017; Koh et al., 2010).

DeepFlight, United States

DeepFlight continues its legacy of innovative underwater technology to enable underwater flight. DeepFlight submersibles are winged submersibles designed to be "positively buoyant" and use hydrodynamic forces from the wings to push the vehicles underwater when moving. The submersibles are low displacement, light weight, designed for speed for commercial markets of superyachts, luxury resort, and private ownership.

In 2017, after many years of self-certification, the company has been working with Lloyds Register to class the new DeepFlight series of submersibles. This classification allows DeepFlight to innovate using composites and other advanced materials, which provide the strength-to-weight ratio to introduce their new generation of lightweight submersibles. DeepFlight launched its new *Super Falcon 3S* submarine, a three-person (one pilot, two passengers) craft designed for tourism operations. *Super Falcon 3S* is based around a composite hull vehicle classed by Lloyds Register rated to a depth of 40 m. The company reported that a survey of component parts has been undertaken in the United Kingdom and the United States, alongside the auditing of fabrication facilities. Both the prototype and production hulls have been successfully pressure tested, and final sea trials of the first of the classed units are taking place in the Maldives in early 2018 (Figure 11).

FIGURE 11

DeepFlight *Super Falcon 3S*.

The first *Super Falcon 3S* is scheduled to be operational in the Maldives in Q1 2018, offering submarine excursions at a luxury five-star resort. A trained pilot will take up to two guests at a time on underwater flights directly from the resort property. Laucala Island in Fiji is also operating an original *Super Falcon* two-person submersible for its resort guests. The company plans to continue expansion of its DeepFlight Adventures to other locations, in partnership with resorts, tour, and water sports operators.

DeepFlight is also continuing to sell its submarines to private owners, and in particular, the superyacht market. In 2017, Princess Yachts ordered a DeepFlight *Dragon* to be integrated into a new build of its 40-m M class yacht. As the smallest and most lightweight two-person submarine on the market, *Dragon* is one of the only personal submarines that can fit on smaller yachts with little or no need for retrofit.

FIGURE 12

DeepFlight *Dragon*.

In additional to opening its first location for DeepFlight Adventures in 2018, the company will also be building several submarines for delivery in 2018–2019 (Hobson, 2018) (Figure 12).

GEOMAR Helmholtz Centre for Ocean Research, Germany

JAGO is a 400-m depth rated two-person submersible dedicated to research in marine sciences, stationed at the GEOMAR Helmholtz Centre for Ocean Research, and is presently the only manned research submersible in Germany. The submersible's relatively light weight (3 tons) and its compact size (3 × 2 × 2.5 m) make it easy to operate worldwide and from a wide variety of support ships that have sufficient crane capacity. *JAGO* was built in 1989, is DNV-GL classed, and has made more than 1,300 dives around Europe and Africa (Figure 13).

In 2017, *JAGO* has undergone a general overhaul, including numerous test dives in the Kiel Fjord with the exchange of new instruments and components. The *JAGO* team is also replacing its thrusters to a rim drive system. In February to March 2018, *JAGO* went on a research cruise to the Cape Verde islands to study

FIGURE 13

GEOMAR *JAGO* submersible.

midwater biodiversity and ecology. The Cape Verde islands are considered a perfect location because the deep sea is close to the islands and pelagic organisms from deep water can be found both close to shore and in shallower waters. Researchers reported making 15 dives down to 400-m depth in the lee sides off the islands Santo Antao and Fogo.

Through 2018, the team plans to exchange its rotatable side thrusters and prepare sampling devices and instruments in preparation for the next two *JAGO* campaigns scheduled to take place in summer from on board the RV *Poseidon*. From end of June to mid-July 2018, *JAGO* will dive at the cold water coral reefs off Norway and from mid-July to mid-August in the North Sea and in the Skagerrak—a new technology testing project that combines submersible dives with hover AUV surveys (Hissmann, 2018).

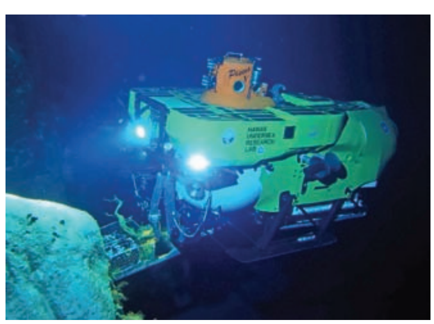
Hawai'i Undersea Research Laboratory, United States

The Hawai'i Undersea Research Laboratory (HURL) is part of the School of Ocean and Earth Sciences and Technology at the University of Hawaii and has been providing unique deep-ocean research capabilities for nearly 40 years. HURL specializes in both research tools and expertise for scientific investigation of the undersea environment. This includes a unique set of manned submersibles, ROVs, and other deep-sea technologies. Most notably, HURL operates the twin *Pisces IV* and *Pisces V* deep submersibles, which are among the longest operating submersibles in the industry. The submersibles are three-person vehicles rated to a depth of 2,000 m and are ABS classed. The deep diving submersibles are the only U.S. deep-ocean national asset that provides the versatility of operating two submersibles side-by-side. The strategic and performance advantages of such an operational concept has been proven in time and again, just as did the Russian *Mir* submersibles in a wide range of unique expeditions (Figure 14).

The university center has faced challenges since the National Oceanic and Atmospheric Administration defunded its submersible program in 2014, but the team has continuously demonstrated creativity and innovation in the service of research. To increase productivity and bottom time per dive day, HURL has transitioned to a default dual subdive model with its *Pisces IV* and *Pisces V* submersibles. The ingenuity of this approach is to boost productivity by getting more work done in fewer days at sea.

FIGURE 14

University of Hawaii *Pisces V* submersible.

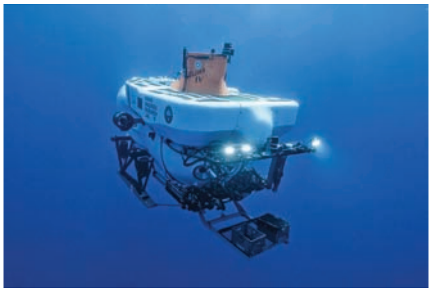


Large support vessels are required for both manned and unmanned systems, and it has become clear that deep-ocean ROV operations have their own challenges when used for deep exploration. The key element for research remains productivity, the ability to get the same level of work done in fewer days at sea or getting more coverage in the same amount of days. The HURL Team has successfully shown over two seasons (2016 and 2017) that twin manned submersibles offer undeniable productivity gains over unmanned ROV systems.

The 2017 National Science Foundation (NSF)-funded Deep Coral Ecosystem Recovery Assessment Project in the Northwestern Hawaiian Islands and Southern Emperor Seamount Chain is an exemplary testimony of MUV mission success. The $3.5M project allocated 90 ship days of which 25 days were used in transit, a total of nearly 4,500 nm. An additional 10 days were lost to unexpected weather outside normal launch margins. The original plans were to explore the terrain by ROV. However, the topography consisted predominantly of current swept, steep volcanic island cores, and vertical carbonate atoll walls with numerous narrow cutbacks and overhangs. Danger and risk were unnavigable for all but the most advanced robotic underwater systems and teams. By mid-November 2017, the survey was successfully completed using the twin *Pisces* submersibles and the HURL team. They availed themselves of the remaining 55 work days to perform a total of 76 submersible dives during which 242 detailed bottom video transects of 500 m each were completed. A total of 1,533 coral samples were collected for genetic and paleooceanographic analysis. The total

FIGURE 15

University of Hawaii *Pisces IV* submersible.



distance covered by the two subs was about 250 km, the average time submerged per dive day was 12 h, and the average time spent on bottom transecting and collecting was 8 h.

At the beginning of 2018, the university announced that it would shut down the submersible operations and divest itself of the assets. The *KOK* research ship is due for recertification by mid-2018, whereas both submersibles remain in ABS class. The two *Pisces* submersibles represent the only U.S. asset capable to deploy a tandem team of submersibles to 2,000 m, with an operations team presenting more than 25 years' experience operating MUVs. This remains a unique asset in the U.S. roster of national capabilities. The HURL reports multiple standing projects for 2018 for the two submersibles. The decommissioning of these assets would reduce U.S. national capabilities to a single MUV (*Alvin*) capable of deep submergence and stand in contrast with international capabilities and developments (Kerby, 2018) (Figure 15).

ICTINEU Submarins SL, Spain

ICTINEU Submarins is a manufacturer-operator based in Barcelona, Spain, founded in 2007 to develop and build the deepest private submersible in operation, the *ICTINEU 3*. This new generation of manned submersible, with a powerful state-of-the-art battery package, can navigate up to 20 nm underwater. The *ICTINEU 3* is designed for underwater exploration, scientific research, and underwater intervention. *ICTINEU* innovations include advanced hydrodynamics, extensive use of smart composites, and high-density, high-power lithium batteries capable of operating at ambient pressure. *ICTINEU 3* was classed by DNVGL, launched in 2013, and is registered by French Maritime Affairs for operation in European waters. *ICTINEU 3* has completed more than 100 dives at sea between 30- and 1,000-m depth.

In 2017, ICTINEU deployed their submersible for an expedition to the Nice Canyon in Côte d'Azur, France. The expedition was organized in cooperation with the Oceanographic Observatory of Villefranche sur mer (OO-CNRS-UPMC) and the research laboratory Géoazur, France. The Oceanographic Observatory of Villefranche is a multidisciplinary research center associated with the University Pierre et Marie Curie in Paris and the French National Research institution CNRS. The mission took plankton observations through the water column, studied the crepuscular benthic communities, as well as coral communities and their relationship to water acidification.

The Géoazur center combines earth, ocean, and space research. Three subjects of particular interest were (1) the Messinian Era in which the Mediterranean basin (sea) dried out and afterward refilled quickly; (2) a study of the −120 m zone where the sea level was during the last glaciation; and (3) an evaluation of the geologic risks on the Nice air-

FIGURE 16

ICTINEU 3 research submersible.

port, which is located near a highly abrupt shelf. The team observed very steep terrain, even steeper and more abrupt than shown by the detailed cartography. Near the seafloor, very dense masses of plankton and krill were observed. Observations confirmed that some species of plankton are abundant in the area, although they are rarely sampled with the usual sampling tools.

In early 2018, the company announced the successful development of the first battery module certified for operation at FOD in a joint venture with Triton Submarines. The new unit, a pressure-compensated lithium polymer battery module producing 148 V DC, 10,36 kWh was developed to extend ICTINEU's existing 6,700-m-rated power unit to a battery capable of diving to any depth, from shallow to FOD. ICTINEU reports the unit is currently undergoing DNV-GL type-approval; the new battery named ITHACA is a maintenance-free, 4,000-cycle-capable plug-and-play battery. Full production of ITHACA is on schedule first deliveries in mid-2018 (Fores & Parareda, 2018) (Figure 16).

Ifremer *Nautile*, France

Ifremer built *Nautile* in 1984, and it was the first of a new generation of

FIGURE 17

Ifremer deep-sea *Nautile* submersible.

FIGURE 18

France's deep submersible *Nautile*, launched from its mothership *Pourquoi Pas?*

deep research submersibles rated to 6,000 m. *Nautile* counts among its achievements 116 dives on the RMS *Titanic* between 1987 and 1998, early thermal vent exploration, and meeting up with *Alvin* at the bottom of the Atlantic in 1987. Although budgets are strained, Ifremer has no plans to replace *Nautile* and projects an extended life program for the pressure hull and periodic technology improvements (Figure 17).

Nautile remained active through 2017 with a scientific expedition on the Mid-Atlantic Ridge from March to April 2017 aboard the research ship *Pourquoi Pas?* During this expedition *Nautile* performed 20 dives to depths ranging from 3,500 to 4,500 m. In December 2017, *Nautile* was deployed on a technical expedition in the Mediterranean. A series of engineering dives to depths of 2,700 m were performed to prepare the submersible for its 2018 season with a series of new and advanced scientific instruments designed for taking samples and perform *in situ* analysis.

In January 2018, *Nautile* was deployed in the Mediterranean for work on the subsea neutrino detector observatory ANTARES, located at a depth of 2,500 m. This is the European equivalent to the North American Sudbury Neutrino Observatory. The *Nautile* performed work at the base of the detector field for the recovery of certain scientific instruments.

In February to March 2018, *Nautile* was scheduled to return to the Mid-Atlantic Ridge for a biological exploration of the hydrothermal vents and has planned 28 dives between 3,000- and 4,000-m depth. The submersible is scheduled for maintenance between April and August 2018, which will include the replacement of the equatorial O-ring sealing the two hemispheres of the personnel sphere. At the end of the year, *Nautile* is scheduled to be deployed on the site for a new underwater observatory called MEUST, which is to replace the existing ANTARES observatory. The *Nautile* will be used to install and deploy new scientific equipment (Ciausu, 2018) (Figure 18).

JAMSTEC *Shinkai 6500*, Japan

Shinkai 6500 is the flagship deep-ocean submersible for the Marine Technology and Engineering Centerof JAMSTEC (Japan Agency for Marine-Earth Science and Technology). *Shinkai 6500* was built in Kobe, Japan, in 1989, a three-person deep-ocean research submersible rated to a maximum depth of 6,500 m. The *Shinkai 6500* is operated from its mothership R/V *Yokosuka* and passed the 1,500 dive mark in 2017, completing its 1,509th dive during the season.

The *Shinkai 6500* had a major overhaul in 2012, the largest upgrade made to the submersible since it was launched. JAMSTEC has initiated a second major upgrade, specifically addressing the remodeling of the personnel sphere. The *Shinkai 6500* was traditionally piloted with a pilot, a co-pilot, and one passenger/researcher. Demands from scientific communities are continuously evolving, and one request was for two researchers to be able to dive together, with a single pilot. Although this has been a traditional operating concept in other countries, JAMSTEC had to make changes to design, instruments, and concepts of piloting to transition to single-pilot operation.

A major remodeling was carried out from 2016 to 2017 to realize the single-pilot changes. The cabin remodeling and overhaul were completed in March 2017. New equipment and instruments had been installed and checked throughout the previous year to help with navigation and operation. JAMSTEC performed several dives in 2017, which allowed shakedown training conducted under simulated one-man pilot operations. Some of the principal operational issues to transition as a single pilot are the concurrent operation of the HDTV camera, operation of the robotic arm to take samples, talking to the surface ship, and managing the recording of the samples taken. Several challenges were extracted from the exercise, and final equipment improvements were made for 2018. JAMSTEC is revising its operation manual and confirms that single-pilot operation is no hindrance. From April 2018 onward, JAMSTEC plans to start single-pilot operation for research dives at well-known research locations (Yanagitani & Onishi, 2018) (Figure 19).

FIGURE 19

JAMSTEC deep-sea submersible *Shinkai 6500*.

Japan Maritime Self-Defense Force, Japan

In September 2017, Kawasaki Heavy Industries launched Japan Maritime Self-Defense Force's (JMSDF) third DSRV built for the Japanese Ministry of Defense. This vehicle is the third DSRV, and it has been 18 years since the second DSRV was delivered in March 2000. Unlike airplane accidents, submarine accidents often have survivors, and rescuing the crew of a disabled submarine is a major concern of modern navies in the world. This technology is more closely related to deep research and commercial submersibles than military submarines. Common traits are the deep depth of operation, its operating crew, and the ability to accommodate a large number of occupants with the ability to reach a stricken vehicle and mate to its rescue hatch.

The JMSDF is the *de facto* navy of Japan, and the new DSRV launch is part of an effort by JMSDF to modernize its undersea capabilities with a fleet of 22 diesel-electric submarines by the early 2020s. This includes a total of 12 new Soryu-class submarines by 2021, with a displacement of 4,100 tons when submerged and Japan's first class of air-independent propulsion submarines. The JMSDF is one of the world's largest navies and the second largest navy in Asia in terms of fleet tonnage. Japan will also become the first nation to equip part of its submarine fleet with advanced lithium ion batteries, one of Japan's top military secrets, in order to improve the submarine's underwater endurance.

Inspired by the Russian Kursk incident, NATO established the International Submarine Escape and Rescue Liaison Office to help with global assistance in submarine accidents. At the same time, with the growing number of nations operating submarines over the past 25 years, the philosophy of collective rescue spread rapidly. Today, many countries collaborate to offset the high cost of developing these submarine rescue capabilities. Multilateral at-sea exercises such as Sorbet Royal bring together NATO members and Pacific Reach brings participants of Asia-Pacific nations. Japan continues to participate in these exercises since the early 2000s. Japan's native submarine production technology and deep submersible capability present a growing national asset as it now seeks to export its technology around the world. Although coordination and standardization challenges exist, in general the NATO countries enjoy a closer working relationship than does the pacific theater. China, Japan, and India face greater challenges balancing international cooperation with national security (KHI, 2018; Fuyama, 2016) (Figure 20).

FIGURE 20

Japan deep submergence rescue vehicle DSRV III.

JFD, UK

JFD is headquartered in Inchinnan, near Glasgow, and has over 30+ years of submarine rescue operation experience with facilities in Singapore, Australia, and Sweden. It has established itself as an international specialist in this field. JFD provides design, manufacture, maintenance, and training services. JFD provides submarine rescue capability to several countries, including the submarine rescue vehicles (SRVs) for the Indian navy.

In Fall 2017, experts from nine allied nations committed submarines, submersibles, rescue vessels, specialist medics, helicopters, and divers for a 2-week-long Exercise Dynamic Monarch. Taking part in the exercise was the JFD-built NATO Submarine Rescue System (NSRS), jointly owned with the United Kingdom, France, and Norway, capable of diving down to a submarine in distress, "mating" with escape hatches, and carrying out an evacuation of the vessel. Submersibles from 11 countries participated in exercises to depths of more than 720 feet. The NSRS, like many rescue submersibles, can be transported anywhere in the world within 72 h (Figure 21).

JFD Submarine Rescue Vehicles

SRV	Nation	Max Depth
LR5 (DSAR-1)	Australia	400 msw
DSAR-5	South Korea	500 msw
DSAR-6	Singapore	500 msw
NSRS SRV-1	NSRS	610 msw
URF	Sweden	450 msw
INDIA DSRV I	India	620 msw
INDIA DSRV II	India	620 msw

FIGURE 21

JFD submarine rescue vehicle DSRV I for the Indian Navy.

In 2017, JFD completed harbor acceptance trials for the first of two DSRVs for the Indian Navy. These two DSRVs are part of a third-generation submarine rescue system developed by JFD to rescue the crew from a distressed submarine (DISSUB). The DSAR class submarine rescue vehicle is capable of diving to deeper depths than previous designs with a crew of three and up to 17 rescuees. Under a £193M contract, awarded in March 2016, JFD is providing two complete flyaway submarine rescue systems including DSRVs, launch and recovery systems equipment, TUP systems, and all logistics and support equipment required to operate the service. The full certified systems are scheduled to be delivered to the customer in June 2018 (JFD, 2018).

National Aeronautics and Space Administration, United States

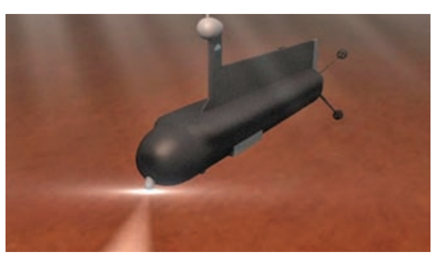
National Aeronautics and Space Administration (NASA) believes that there may be life on a moon called Titan, as it is the only place in our solar system where surface liquids have been found—and where there is water, there is chance of life. Their proposed submersible would be designed as an autonomous research and science vehicle aimed at the study of extraterrestrial seas.

NASA's Cassini space probe was the first satellite designed to orbit around Saturn. Until then, very little was known about any of its moons, including Titan, the largest moon, which is roughly the size of Mercury. Cassini mapped the moon's surface and even sent out a probe, called the Huygens probe, to the surface of the moon. The discoveries were extensive. Data from the Cassini-Huygens probe revealed Titan has seas of liquid methane and ethane. In 2008 the 400,000 km^2 ocean was named Kraken Mare and thought to be the largest body of liquid on Saturn's moon. The temperature of the methane ocean is −184°C. Today, NASA is studying possibilities of exploring Titan's oceans with a specially designed submersible vehicle (Figure 22).

Several probe ideas have been proposed, and NASA is considering a fully autonomous submersible. The space agency has a conceptual design for the Titan submarine and is looking at a mission challenge within the next 20 years. Titan is 886 million miles from Earth, so it would require a significant spacecraft to get the submarine to destination. One of the challenges operating a submersible vehicle in such cold environments is the problem of bubbles. Any system based on heat-generating machines is likely to generate nitrogen bubbles, which can lead to maneuvering problems.

FIGURE 22

NASA Titan submersible concept.



NASA says: "By addressing the challenges of autonomous submersible exploration in a cold outer solar system environment, Titan Sub serves as a pathfinder for even more exotic future exploration of the sub-surface water oceans of (Jupiter's moon) Europa." If such a mission moves forward, it would represent a new frontier of space exploration as well as research submersibles (Whigham, 2018).

NIOT, India

The NIOT, based in Chennai, was established in November 1993 under the Ministry of Earth Sciences, Government of India. The institute's primary aim is to develop indigenous technologies for deep-ocean exploration and the harvesting of nonliving resources such as polymetallic manganese nodules, marine gas hydrates, hydrothermal sulfides, and cobalt crusts. These resources are typically found between 1,000 and 5,500 m water depths in the Central Indian Ocean Basin, Bay of Bengal, and Arabian Sea.

Over the past 20 years, NIOT has developed several underwater vehicles. These include a 6,000-m depth rated ROV (*ROSUB 6000*) qualified and tested to 5,289 m in the Central Indian Ocean Basin. The ROV explored for natural gas hydrates at depths of 1,000 m in the Krishna Godavari Basin, polymetallic nodules at depths of 5,000 m in the Central Indian Ocean Basin, and hydrothermal sulfides at the Rodriguez Triple Junction in the Central Indian Ridge system at a depth of 2,813 m. NIOT also developed other submersible systems such as a 6,000-m depth rated *in situ* soil tester, a 3,000-m depth rated autonomous coring system, and a 500-m depth rated underwater integrated mining system. For polar research, NIOT also developed a 500-m depth rated ROV (*PROVe*).

The next step in the development is to utilize the expertise gained over the past two decades to develop a deep-ocean manned submersible—*Matsya 6000*, with a depth capability of 6,000 m. The NIOT *Matsya 6000* is designed for carrying three persons with an operational endurance of 12 h and emergency endurance of up to 72 h. The design follows a traditional architecture with the objective to leverage the newest technologies to keep the submersible weight less than 20 tons. The 6,000-m rated cabin is based on a 2.1-m diameter titanium alloy personnel sphere, made of two halves welded together. Hydrodynamics are aimed at achieving ascent and descent rates of 30+ m/min, allowing the submersible to reach full depth in 3 h. Study work continues on view ports, life support systems, reliable battery configuration, and launching and recovery systems.

FIGURE 23

India NIOT deep-sea research submersible *Matsya 6000* concept.

No MUV systems currently exist in India. NIOT continues to develop expertise and capacity in the development of India's manned submersible technology with possible joint partnership of national and international organizations (Ramadass & Ramesh, 2018) (Figure 23).

Nuytco Research Ltd., Canada

Nuytco Research Ltd. builds a wide range of manned submersibles in North Vancouver, Canada. The submersibles include the single occupant *Deepworker* and two-person *Dual-Deepworker* vehicles rated to 600 and 1,000 m, a five-person tourism submersible *Curasub*, and the *Orcasub* personal vehicle. Nuytco also manufactures the EXOSUIT, an advanced version of the NewtSuit, which is an ADS system designed and classed to Lloyds Registry.

In 2017, Nuytco made several expeditions, sending submersibles to Brazil and diving for a month at the mouth of the Amazon River. Later in the year, Nuytco completed a contract in California for fisheries research. At the beginning of 2018, a full crew and two *DeepWorkers* went on a month-long expedition in Antarctica for Greenpeace, until the first week of February. Greenpeace released many photos and video clips as it called for a large ocean sanctuary for the newly discovered habitat. Greenpeace, based in Amsterdam, is calling for a sanctuary area covering 700,000 square miles (1.8 million km^2) to be set up in the Antarctic to keep species including whales and penguins safe. Proposals for the sanctuary have been submitted by the European Union and to be considered when the Antarctic Ocean Commission convenes in October 2018.

FIGURE 24

Nuytco *DeepWorker* submersibles atmospheric dive suit.

Nuytco also reported working for the U.S. Navy's Office of Naval Research (ONR) on a new version of the submarine rescue system that was originally designed and built for the U.S. Navy and Australian Navy, based on a new large, all-electric work-class ROV, called the *NewtROV*, adapted to accept a one-atmosphere personnel conveyance system (Nuytten, 2018) (Figures 24 and 25).

FIGURE 25

EXOSUIT atmospheric dive suit.

OceanGate, Inc., United States

OceanGate, Inc., is a privately held company in Washington State established in 2009 for the development, manufacture, and operation of manned submersibles for commercial, scientific, and tourism projects. OceanGate owns and operates the five-person *Antipodes* MUV rated for 300-m depth and *Cyclops 1*, a five-person submersible rated to 500 m. The main thrust of the company's activity is the development of a next-generation experiment based on composite materials for deep-ocean operation. Developed as *Cyclops 2*, the new submersible was launched at the end of 2017 as Titan, designed for a depth of 4,000 m with space for five occupants. The focal point of the new design is a composite laminate pressure hull, a large acrylic viewport, and a specialty designed launch and recovery platform for both near-shore and offshore operation.

Titan features a single, large viewport, and its carbon fiber and titanium construction is designed to make the submersible lighter than traditional deep-sea submersibles. It will be outfitted with external 4K cameras, multi-beam sonar, laser scanner, inertial navigation, and an acoustic synthetic baseline positioning system. In parallel with the new submersible development, OceanGate plans to mobilize a new subsea launch and recovery platform. The two elements are intended to work in tandem to form the Titan integrated diving system. The platform will be used to launch and recover the sub and serve as a floating platform for service and maintenance. The integrated system is designed to eliminate the need for A-frames, cranes, and divers, allowing expedition crews simpler, low-cost deployment option in remote locations.

Titan was launched in February 2018 in the waters around Everett, Washington, for 2 months of testing in a series of engineering dives to nominal depths of <300 m. Titan is an experimental design incorporating the largest carbon fiber and titanium pressure vessel, the first ever constructed for external pressure; therefore, factory testing and the validation program are critical. The company has invested 6 years of design and testing of this pressure vessel design in partnership with technology organizations such as the Applied Physics Lab at the University of Washington and the Boeing Company. The partnership provides OceanGate extra technical expertise and confidence for innovation, which incorporates a hull monitoring system to determine the early onset of hull failure and detect potential longer-term fatigue and undetected damage over the life of the pressure vessel. This system is based on nine separate acoustic sensors and 18 strain gauges to measure all mechanical loading of the hull using both passive and active measurements to compare with historical performance at depth. The objective is active monitoring to permit more efficient designs, requiring lower safety factors than used in traditional design techniques and thereby saving weight (Figure 26).

Because of the nonconventional nature of the design, OceanGate is not pursuing classification by IACS class societies. Instead, it has developed a test program modeled on the aircraft test industry where performance envelopes are systematically increased based on a thorough review of performance data from prior tests. While in the Bahamas, the factory acceptance tests are scheduled to conduct multiple dives to 4,000 m to validate the operations and robustness of its hull design with real-time hull health monitoring, its large viewport, the control, propulsion and battery systems, sonars, laser scalers, its inertial navigation system (iXBlue Phins INS), 4K cameras, and other systems. OceanGate reported that the deep diving will be tested gradually toward its goal of 4,000 m, ascertaining the health of all components and systems before diving deeper. The company acknowledged that if unexpected limitations are encountered during the trials, the submersible could be derated to a level deemed safe by its engineering department.

Titan was transported to Marsh Harbor in the Bahamas for deep water testing in late April 2018. The transport and rough weather during the transit caused both damage to the submersible's electronics and caused delays to the testing schedule. The company announced in May that, due to these delays, the 2018 planned Titanic Survey Expedition would be postponed (Rush 2018).

FIGURE 26

OceanGate Titan submersible and launch platform.

Pisces Submarines, United States

Pisces VI is a sister vessel to *Pisces IV* and *Pisces V* operating in Hawaii. The submersible was acquired by Pisces Submarines in 2015, located in Salinas, Kansas, and is in the process of refurbishing the submersible. Just like its sister vehicles, *Pisces VI* is a three-person research submersible that was designed and built by Hyco International Hydrodynamics of North Vancouver, Canada, in 1976, with a maximum operating depth of 2,000 m (6,560 feet). The vehicle has a 2.1-m hull diameter, made of HY-100 steel with three forward-looking 6-inch acrylic viewports. When completed, *Pisces VI* will be the deepest diving privately owned submersible. The submersible will maintain an operational depth of 2,000 m, hold one pilot and three observers, and is projected to weigh only 15,000 lb. The design is also focused on streamlining the dimensions in order to fit, along with all support equipment, inside a 20-foot shipping container. The company's mission is to provide low-cost deep submersible services for the science and film industry, using *Pisces* as an underwater platform for exploration and education.

In 2017, the refurbishment of the cabin, the main ballast tank, and frame configuration was completed. Several modifications and additions are planned, which include battery pack, ballast air, the variable and main ballast tank arrangement, the thruster arrangement, the interior arrangement and mounting method, the fairings, and its transport method to ensure it fits inside a standard ISO container. The company also plans upgrades on the electronics to include auto pilot, GPS navigation, a retractable science basket, and a lateral thruster system. The company reports operation expected to commence in 2019 (Waters, 2018) (Figure 27).

FIGURE 27

Upgraded *Pisces VI* submersible concept.

Rainbowfish Ocean Technology Co., Ltd., P.R. China

Rainbowfish Ocean Technology Co., Ltd. is based in Shanghai, China. The company's objective is to lead research in deep-sea technology, industrialization, and marketing within China and internationally. Of special interest is the challenge of hadal zones extremes and creating technology to explore to FOD. Rainbowfish is the commercial partner of the Hadal Science and Technology Research Center (HAST) of Shanghai Ocean University, which was established in 2013. Rainbowfish and HAST announced in 2016 its plans to challenge the 11,000-m depths with plans to launch a deep research manned submersible rated to FOD (Figure 28).

Supported by Shanghai Ocean University, Professor Cui Weicheng set up the first Hadal Science and Technology research center in China with its goal to develop new frontier deep-sea technology to promote HAST to become a world-famous research and design institution. This cooperation between Rainbowfish and HAST was created to connect scientists and entrepreneurs, utilizing both national support and private investments. At its core is the development of a world-class floating laboratory for hadal science and technology. The project was scheduled in two phases. The first phase focused on the construction of a new 4,800-ton research mother ship, *Zhang Jian,* and the R&D engineering for the *Rainbowfish11000* manned submersible. The second phase plans a series of vehicle tests to FOD, starting with science landers, followed by a new unmanned autonomous remotely operated vehicle (ARV), and finally leading to the construction and sea trials of the FOD manned submersible. Rainbowfish aims to reach the depth of 11,000 m in the Mariana Trench, which would mark the first time a team of three crew and scientists reach the floor of the Mariana Trench.

FIGURE 28

Rainbowfish research ship *Zhang Jian*.

In December 2016 to February 2017, Rainbowfish made its first research cruise aboard its research ship *Zhang Jian,* deploying a set of three FOD landers. All three landers reached the seafloor at the Challenger Deep and performed successfully. The unmanned ARV system was also deployed and reached a maximum depth of 6,300 m, hampered by some technical difficulties. The team returned to the lab to improve the ARV design and started the design of the FOD manned submersible vehicle. Through 2017, the major research was focused on the personnel sphere. Rainbowfish engineers elected for a two-part Maraging Steel hemisphere design, like that used on the Russian *Mir* submersibles. In April 2017, the Finnish foundry Tevo Lokomo Ltd. completed its delivery for the hull after successful pressure testing at the Rainbowfish laboratory in Shanghai. The laboratory has several test chambers, including three chambers rated to 140 MPa, one chamber rated to 180 MPa, and an open test tank 10 m × 20 m 7 m deep.

During 2017, two areas of special focus involved the testing of the acrylic windows and the syntactic foam, due to the desire to have three viewports in the personnel sphere, the size and thickness of the windows was a concern. Based on the ASME PVHO calculations, the window thickness became too thick and a newly designed smaller configuration was tested based on a smaller included angle from the standard 90° conical frustum window. The test results failed to confirm and validate the model. Rainbowfish reported that they start the manufacture of the manned cabin after the successful testing of the window model. Similarly, testing of the syntactic foam material available nationally does not meet the pressure testing to the desired safety factor of 1.5× maximum operating pressure. The company projects to complete the FOD submersible by 2021 (Cui, 2018).

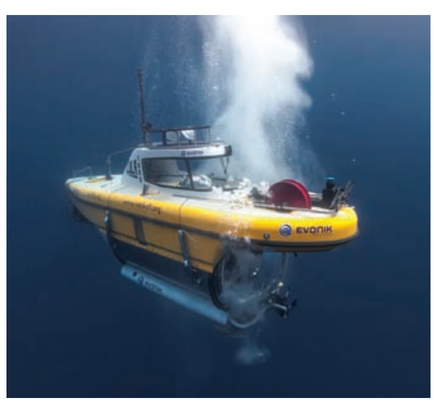
Rebikoff-Niggeler Foundation, Portugal Azores

LULA 1000 is a three-person, 1,000-m rated research submersible operated by the Rebikoff-Niggeler Foundation (FRN). The FRN is a Portuguese nonprofit organization for marine science located on the island of Faial, Azores. Since 2000, Kirsten and Joachim Jakobsen dive deep around the Azores. In 2017, the team discovered and made multiple dives to document the wreck of the *U-581*, a German U-boat found at a depth of 870 m off Pico Island. FRN produced a video documentation of the wreck itself and coral colonies that settled on it, as well as on the habitat near the wreck. The expedition took still images for a photo mosaic of the wreck using an in-house custom-built camera for photo mosaicking that could integrate the picture in the sub (Figure 29).

Instrumental to the U-boat discovery was the use of multibeam and sidescan sonar working in great depth when the search started in 2016. *U-581* left for the Azores with the order to sink the British vessel *Llanggibby Castle*, which, on February 2, 1942, had to leave Horta harbor on the island of Faial/Azores. The British destroyer HMS Westcott detected *U-581* and threw depth charges. The impact of those charges caused severe damage to the U-boat, and the commander gave order to the crew to abandon and sink the *U-581*. *U-581* sank in the morning hours on 2nd February 1942, south of Pico Island. Four men died at surface from depth charges, and 41 men were rescued and became prisoners of war. After analyzing German and British reports about the sinking, the team defined a search area of 4 × 8 nautical miles. A first-phase multibeam sonar was used to produce bathymetric 3D charts of the search area. However, because of seamounts in the search area, the sidescan sonar could not be used and the position of the wreck was established with the submersible, producing high-resolution video images. As Joachim Jakobsen describes, “The final discovery was made by looking out of the large acrylic viewport of our research submersible. In the end, we were also very lucky. We had been following a deep-sea fish for filming on this dive. We followed that fish from 800 m to 870 m of depth. Suddenly, we noticed a long cigar shaped echo on the onboard sonar of our submersible. We approached and finally had a breathtaking view to the cannon and the tower of *U-581*.”

FIGURE 29

FRN research submersible *LULA 1000*.



The wreck represents a valuable object for studies on cold-water corals and the conditions that make possible the creation of coral reefs in great depth. Cold-water corals are considered vulnerable ecosystems. Until now, little is known on the growth rate of such corals. Some species can become several hundreds or even several thousands of years old. Being that the exact date of sinking and thus the maximum age of any colonizing organism is known, valuable conclusions may be drawn from this warship wreck that became a hotspot of deep-sea coral life.

During 2017, *LULA* also dove extensively in research projects for mapping of deep-water habitats off the Azores Islands. The submersible operates in near open ocean conditions and was designed for high-quality deep-sea filming. In the fifth year of operation, the *LULA 1000* continued to work on habitat mapping along the islands’ often steep slopes. This included documentation of deep-sea fauna and habitats such as sponge fields and coral communities and collection of base data on the deep-water habitats.

LULA 1000 also deployed for deep pelagic dives in the feeding grounds of sperm whales. The dives proved to be extremely challenging and interesting, a research activity that carries on in 2018. The continuous expedition aims to understand what sperm whales find to feed on, and the team reports that the extended bottom time offers the opportunity to film unique and never-seen pelagic species. Part of this incredible footage includes the filming of the whalefall featured on the *Blue Planet II* deep episode showing a large number of sixgill sharks feeding on a dead sperm whale (Jakobsen & Jakobsen, 2018).

Roatan Institute of Deepsea Exploration, Stanley Submarines, Honduras

The Roatan Institute of Deepsea Exploration (RIDE) was established by Stanley Submarines, operating in Roatan, Honduras, since 1998. When he was 9, Karl Stanley dreamt about submersibles and launched his first winged, gliding submersible the week he graduated college. The deep submersible *Idabel* was completed in 1998, operating off the island of Roatan, where it still takes tourists, film makers, and scientists on dives down to 2,000 feet.

Although the *Idabel* design was never formally reviewed by a class society, the submersible was extensively tested and validated at sea over many years. RIDE is one of three deep diving submersibles in the world offering trips on a continual basis. Through his work diving with the public, research scientists, and personal exploration, Karl Stanley has accumulated a remarkable dive log, piloting over 2,000 dives, ranging from 500 to 2,000 feet, and over 5,000+ h at depth.

In 2017 and 2018, RIDE continued to fulfill its mission statement by providing the public with cost-effective, direct access to the deep ocean. The company completed the construction of a new watercraft called the subsled, designed to dock with *Idabel* and provide a hydrodynamic bow and additional ballasts for long-distance towing. This increased the maximum towing speed from 3.5 to 7.5 knots. Since the submersible is launched from shore, this innovation drastically increased its range of exploration. On its first mission with the sled, *Idabel* was towed to an underwater feature 14 miles away. Docking and undocking were safely completed in the open ocean in 4-foot seas. In 2017, RIDE added a custom fish collection device and a temperature and depth recorder to monitor ocean temperatures on 100+ dives per year. The new animal collection device used an anesthetic solution, when administered to a target fish, dazed or sleeping, the fish is sucked into a collection tank. The system was successfully deployed on six dives with researchers from the University of Washington and the Smithsonian, who also funded the project. The research dives collected over 30 fish specimens: three entirely new species, 7–10 had only been visually observed in the Caribbean, and the remaining samples were first-time collections in the Mesoamerican Reef. Finally, at the end of the year, *Idabel* received several system upgrades, most notably an autopilot system (Stanley, 2018) (Figure 30).

FIGURE 30

Idabel submersible with towing sled.

SEAmagine Hydrospace Corporation, United States

SEAmagine Hydrospace Corporation is a California-based company established since 1995 and is a leading designer and manufacturer of small manned submersibles with over 12,000 dives accumulated by its existing fleet. The company produces two- to six-person models with depth ratings ranging from 150 to 1,500 m for the professional, scientific, and superyacht markets. All SEAmagine submersibles are classed by the ABS and are based on the company's patented technologies.

The company has been producing its two- and three-person Ocean Pearl models for many years and a new three- to six-person Aurora submarine product line rated up to 1,500 m. The Aurora design is based on a hyperhemisphere acrylic cabin with an enhanced field of view by moving the access hatch away from the top of the window into a separate compartment behind the main cabin. This design's ability to tilt at surface provides a stable platform that does not require forward pontoons that restrict peripheral viewing.

During 2017, SEAmagine started the formal submersible pilot and crew training for 10 officers from the Argentinian Coast Guard, called the "Prefectura Naval." The classroom theory classes were given in California, and the practical submersible diving exercises were performed in Argentina with the ABS-classed,

FIGURE 31

SEAmagine Aurora 3C luxury submersible.

350-m depth rated, two-person Ocean Pearl model that was delivered there in 2016. All practical dive training was performed in the 440-m deep fresh water lake called Nahuel Huapi near Bariloche in the Andes of South Patagonia, Argentina. A total of 65 dives were performed during the training down to maximum depth of 300-m deep during that training period.

SEAmagine also relocated to its new larger offices and shop facilities in 2017 from Claremont to nearby Upland, California. Among other projects, the company is currently under contract for the fabrication of two of its new Aurora submersible models with one vessel depth rated to 460 m and the other to 1,000 m. Both new submersibles will be classed by the ABS and approved by the Cayman Island Shipping Registry Flag State. The deliveries of these new Aurora submersibles will take place in 2018 and 2019 (C. Kohnen, 2018) (Figure 31).

Submergence Group, LLC (United States) and MSubs Ltd. (United Kingdom)

Submergence Group and MSubs Ltd. provide manned and unmanned submarines and vehicles for defense, research, and commercial sectors. MSubs is an extension of Marlin Submarines, established in 1986, which built up a portfolio of manned submersibles ranging from tourist submarines to swimmer delivery vehicles and submarine rescue vehicles. In 2016, Lockheed Martin and Submergence Group announced a partnership to build, integrate, test, and deliver three dry combat submersibles (DCS) to U.S. Special Operations Command (USSOCOM). The DCS is designed to support two operators (pilot and navigator) plus up to six swimmers with the ability to lock them out and in.

FIGURE 32

MSubs S351 DCS.

The DCS contract will supply a new class of seal delivery combat submersibles to operate at greater depths and with longer endurance. In 2017 and 2018, Submergence Group and MSubs continue to support SOCOM and WARCOM with S351 submersible operations and the construction of the three, new DCSs. The original S301 prototype has been the subject of a CRADA (Cooperative Research and Development Agreement) with SOCOM and continues to be used as an R&D asset for the Navy, now entering its 10th year of operations (Phaneuf, 2018) (Figure 32).

Triton Submarines, LLC, United States

Triton Submarines was formed in 2008 in Vero Beach, Florida, and is a leading manufacturer of manned submersibles for recreation, science, archeology, exploration, and filming. Triton offers a comprehensive line of products from one- to seven-person models designed around state-of-the-art transparent acrylic pressure hulls. Their most popular submersibles range in depth rating from 500 to 1,000 m (1,650–3,300 feet). The company also promotes acrylic hull designs capable of diving to 2,280 m (7,500 feet) with three-person capacity and a design capable of achieving FOD of 11,000 m (36,000 feet).

All Triton submersibles are classed either by the ABS or DNV-GL. Triton submersibles have been used in numerous research and scientific missions around the world, ranging from local work in Florida and the Bahamas to expeditions in remote corners of the Pacific. Highlights of missions over the past 5 years include capturing the first-ever live images of the giant squid in its natural habitat (Bonin Islands, Japan); a deep-sea shark documentary for NHK and the Discovery Channel in Sagami Bay Japan; the first dives in Antarctica in over 50 years (since Cousteau in the 1960s); David Attenborough's dive on the Great Barrier Reef; a BBC series in the Galapagos; and a science expedition in Bermuda for the Nekton marine science organization.

To date, Triton has delivered 12 submersibles including two Triton 1000/2s, which are a two-person capacity unit rated to a depth of 1,000 feet; eight Triton 3300/3s, which are capable of diving to 3,300 feet for three people; a Triton 1650/3 LP superyacht submersible rated to 1,650 feet for three people; and a Triton 3300/1 MD (minimum displacement) with a diving depth of 3,300 feet for one person. The company has three submersibles currently in construction that are to be announced shortly.

Triton submersibles are used for recreation, scientific research, and filming. The most active submersible is a Triton 3300/3 named *Nadir*, which is based aboard the vessel M/V *Alucia*. *Nadir* has been used to make numerous movies and documentaries. In 2017, *Nadir* was used to film the *Blue Planet II* series. The pair of Triton submersibles based in Malta includes a Triton 3300/3 and a Triton 3300/1 used for scientific and historical research in the Mediterranean, including filming of the HMHS Britannic, sister ship to the RMS *Titanic*. Both Triton 1000/2 submersibles are used for scientific research and documentary filming by the Global Sub Dive group. These two Triton submersibles are based aboard the M/V *Go America* (Figure 33).

In the period from January to December 2017, Triton completed construction of the eighth Triton 3300/3 and a new model, the Triton 1650/3 LP. The Triton 1650/3 LP is a "low profile" model, which is designed to easily fit and be supported by superyachts. Plans are to complete a second Triton 1650/3 LP in 2018. The company also signed a contract for a new six-man submersible, the Triton 3300/6, rated to 1,000 m (3,300 feet). In September 2017 at the Monaco Boat Show, Triton announced its Project Neptune, a joint design collaboration with Aston Martin for a three-person, 500-m depth rated submersible. Design work is ongoing, and construction is scheduled to be completed in 2019 (Haley, 2018).

FIGURE 33

Triton six-person 3300/6 deep touring submersible.

U-Boat Worx, Netherlands

U-Boat Worx was founded in 2005 as a manufacturer of private and luxury submersibles in the Netherlands. The company has a wide range of models ranging from one to nine people and operates to depths up to 1,700 m. U-Boat Worx submersibles are designed, engineered, and built to DNV-GL classification. U-Boat Worx entered in a partnership with Exa Limited, part of the Asian conglomerate Genting Group, in 2013, which enabled the company to increase production and reduce delivery times. In 2015, U-Boat Worx produced its first private submersible for a cruise ship. This was followed by a C-Explorer delivered for the *Crystal Esprit* cruise ship and *Genting Dream*.

The company has developed a range of acrylic submersibles for the private and luxury market, which extends into the tourism market with vehicles of larger capacity. The increasing thicknesses of cast acrylic has enabled large acrylic submersibles to reach ever deeper depths. This is led by specialized capabilities developed by acrylic manufacturers such as Evonik in Germany and Blanson Ltd. in the United Kingdom. U-Boat Worx developed a production line approach to build a wide range of models for private explorers, superyacht owners, research vessels, and commercial tourism operation on board of cruise liners. The U-Boat Worx includes the C-Explorer line of two- and three-person submersibles rated to 300-m depth; the Super Yacht Sub designed as a three-person model rated to 300 or 500-m depth; and the HiPer Sub models designed as high-performance vehicles for two- or four-person capacity but limited to 100-m depth rating.

U-boat Worx has developed two new model series with innovative designs, the C-Researcher for scientific exploration of the deep and the Cruise-Sub for leisure and tourism. The C-Researcher 2 and 3 offer two- and three-person capacity with a maximum depth capability of 3,000 m for a two-person model and 2,500 m for a three-person model. The Cruise-Sub presents a series of multipassenger submersibles ranging from capacities of 5–11 persons, ranging in depth capacities from 200 m for up to 11-person models to 1,700 m for five-person models (Figure 34).

In 2017, U-Boat Worx delivered two Super Yacht Sub 3 models to undisclosed clients. It also delivered two C-Explorer 5 submersibles for operation on the new *World Dream* cruise ship, sister ship to the *Genting Dream*. The company reports having several Cruise Sub models in production

FIGURE 34

U-Boat Worx multipassenger cruise submersible.

with its flagship model, the seven-seat Cruise Sub with a depth rating of 1,140 m. Construction is ongoing, and pressure testing of dual acrylic hyperhemisphere hull with a Titanium mid-section has been successfully completed under DNVGL rules and inspections.

U-Boat Worx reported its suboperations diving at locations around the world, including Thailand, Malaysia, Philippines, Indonesia, Maldives, Seychelles, Japan, Antarctica, Mediterranean, Caribbean, Scotland, Russia, Greenland, and Norway (Hasselman, 2018).

U.S. Navy SRDRS and PRM *Falcon* DSRV, United States

In 2008, the SRDRS replaced the U.S. Navy's two older DSRVs *Mystic* and *Avalon* as the primary deep-sea rescue vehicle for submarine rescue. Unlike *Mystic*, which could only be transported via modified submarines, the SRDRS was designed as a "fly-away" system that can be mobilized via military or civilian transport aircraft and installed aboard a variety of VOOs upon notification of a submarine in distress. The SRDRS system consists of (1) the DSRV *Falcon*, a tethered, remotely operated PRM, along with its launch and recovery system, and (2) the Submarine Decompression System that allows rescued submariners to remain under pressure during the transfer from the PRM to hyperbaric treatment chambers aboard the VOO. The TUP capability allows sailors to transfer from a pressurized compartment aboard a disabled submarine to a recompression chamber aboard the rescue ship to begin decompression. This is designed to increase the chances of survival and avoid life-threatening consequences of decompression sickness (Figure 35).

FIGURE 35

U.S. Navy *Falcon* rescue submersible.

The *Falcon* is rated to a depth of 2,000 feet and designed to mate to a disabled submarine at a list and trim angle of up to 45°. The *Falcon* has a crew of two and can transfer up to 16 personnel at a time. The older DSRVs (*Mystic* and *Avalon*) operated on batteries and required 2-h battery recharge between dive cycles. The PRM is surface powered via an umbilical and can operate continuously. The SRDRS is operated by the Undersea Rescue Command (URC) homeported in San Diego, a component of Submarine Squadron 11 in Point Loma, California, which is also home to four Los Angeles-class nuclear-powered fast-attack submarines. Phoenix Holdings International is contracted to maintain and operate the SRDRS and provide support maintenance under U.S. Navy certification requirements. These efforts include the support and maintenance of the Submarine Rescue Chamber (SRC) rescue chamber and the four 2,000-foot rated ADS systems. These ADS systems were decommissioned in 2017 and replaced with an ROV system.

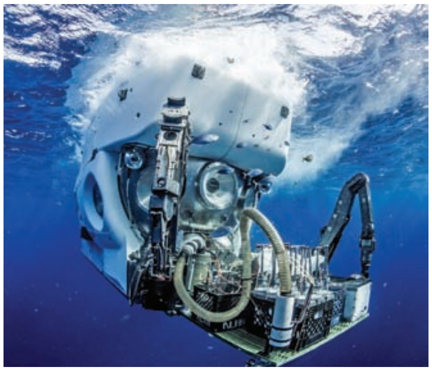
Although the PRM *Falcon* has been operational for many years, in 2017 the complete SRDRS system was installed aboard the URC's training ship. This was the first time the Navy fully assembled the TUP capability to connect the PRM to the decompression chambers. Testing is ongoing to support URC's operational training and for the certification of the Navy's deep-sea submarine rescue capability. In November 2017, the URC also deployed to Argentina as part of the American response to a missing submarine and its 44 sailors. Three U.S. Air Force C-17 Globemaster III and one U.S. Air Force C-5 Galaxy aircraft transported the SRC and an ROV. Eight aircrafts were mobilized, the first arriving in Argentina within 43 h and the last within 120 h. Two VOOs were mobilized, the first as a search and ROV support vessel and the second as the SRC rescue chamber support ship. The mobilization time to set up each ship was 20 h for the ROV ship and 68 h to install the SRC system. Search parties never found the *ARA San Juan*, and the team returned to California in December. The SRC is a McCann rescue chamber designed during World War II and is still used today. The SRC can rescue up to six persons at a time and reach a bottomed submarine at depths of 850 feet. It is operated by two crew members and mate with a disabled submarine by sealing over its hatch, allowing sailors to safely transfer to the rescue chamber (Hazenberg et al., 2018).

WHOI, United States

The WHOI's Deep Submergence Operations Group operates the *Alvin* submersible. Launched in 1964, *Alvin* has seen several overhauls. Since 2012, the latest upgrade was completed, which included a new personnel sphere rated to 6,500 m. Today, the deep submergence vehicle *Alvin* is America's advanced, state-of-the-art, deep diving submersible available for direct observation and investigation

FIGURE 36

Woods Hole deep-sea research submersible *Alvin*.



of the deep ocean. *Alvin* provides a front-seat, first-person diving experience that is unmatched by remote imaging systems, enabling excellent investigations of deep-sea environments. *Alvin*'s numerous sensors provide large quantities of high-quality data, and new digital network interfaces allow integration of unique scientific devices and sampling tools. Digital images, HD video, and dive data travel over a new fiber-optic computer network for superb image collection and advanced systems monitoring and data analysis (Figure 36).

Alvin recently completed the most extensive period of systems upgrades and improvements in its 50-year history. This included a new, larger personnel sphere with an ergonomically designed interior and enhanced external viewing, digital command and control system, improved propulsion system, advanced imaging system capable of high-definition still images and 4K/HD video, new digital scientific instrument interface system, new science workspace and manipulator configuration, and numerous other improvements.

Alvin is owned by the U.S. Navy's ONR and operated as a part of the National Deep Submergence Facility at the WHOI. In 2020, *Alvin* will complete the final systems conversions for operations to 6,500 m, enabling access to over 95% of the world's oceans (Strickrott & Tarantino, 2018).

Conclusion

The MUV sector is an active international industry that is moving forward at a fast pace and continues to build momentum year by year. Despite a prevalence of unmanned systems in the subsea sector, MUV design and construction is growing and driven by new market trends and new technologies. Commercial growth is specifically in the luxury yachting industry and ocean expeditions. The tourism sector is finding new high-end expeditions markets, and deep-ocean exploration continues to be of national interest in Asia. Developments in materials, batteries, and instruments offer an increased array of opportunities for new organizations to develop new underwater vehicles, both for classed designs or experimental concepts. Size and weight remains a focus of attention throughout to find better, more efficient ways to transport MUVs and increase the range of operation. Classification and certification organizations continue to support a well-developed framework of design and construction safety rules; however, although little guidance exists for safety of operation of MUVs, there is ongoing industry development to organize best industry practices under an MUV operations consensus standard. The foundation of that standard has been provided in this paper and will serve as a basis of clearly identifying the capabilities and safety background for all types of submersibles.

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