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Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines

The greatest potential risk from turbine operation continues to be perceived by regulators and other stakeholders to be that of marine animals colliding with turbine blades. These potential interactions are the most difficult to observe using common oceanographic instruments and must be undertaken in parts of the ocean where fast moving water and high waves make studies challenging. However, our collective understanding of the effects of marine renewable energy (MRE) devices on marine animals and their habitats has improved through monitoring and research since the publication of the *2016 State of the Science* report (Copping et al. 2016).

10.1. BACKGROUND TO ENVIRONMENTAL MONITORING TECHNOLOGIES AROUND TURBINES

Technological advancements in different instrument classes, the integration of instruments on subsea monitoring platforms, and improvements of methodologies have increased our understanding of the effects that tidal energy turbines and wave energy converters (WECs) have on marine organisms. Despite these advances, monitoring challenges remain with respect to the durability of monitoring equipment in harsh marine environments, power availability/management of integrated monitoring systems, and continuous data collection, storage, and analysis. This chapter focuses on the state of the science in environmental monitoring technologies and techniques, in particular (1) the instrument classes used for monitoring MRE devices (Section 10.2)[1], (2) the challenges of monitoring around MRE devices (Section 10.3), and (3) integrated monitoring platforms that are currently used to monitor MRE devices (Section 10.4). This chapter also provides an overview of lessons learned from monitoring activities (Section 10.5) and recommendations for quality data collection, management, and analysis (Section 10.6).

An additional challenge to developing and operating environmental monitoring instruments and platforms around MRE devices is the need to have available instrumentation packages that can be safely and effectively used by MRE developers around active wave or tidal projects. MRE developers invest time and resources to design against device failure; the same investments are likely needed for monitoring instruments. There is a need to design and implement simple, robust environmental monitoring packages because many consenting/permitting (hereafter consenting) decisions are contingent upon the operation and provision of data streams from the instruments. Many of the instruments described here were developed for research purposes; additional effort will be needed to further marinize and harden the platforms and instruments to assure that the engineering designs are capable of withstanding the purpose for which they may be used in the high-energy waters where the harvesting of tidal and wave energy is planned.

1. Mention of commercial instruments or other equipment and software throughout this chapter is meant to illustrate the gear in use and does not constitute endorsement of any commercial products.

10.2. INSTRUMENT CLASSES USED FOR MONITORING MRE DEVICES

A suite of environmental monitoring instruments has been used to monitor the potential environmental effects of MRE devices. The most common instrumentation used to document interactions of marine animals and habitats with MRE devices include passive acoustic instruments, active acoustic instruments, and optical cameras, while other instrumentation is used to help define the physical environment in which these interactions may occur. Here, we provide an overview of the different classes of instrumentation used for monitoring marine animal interactions with MRE devices.

10.2.1. PASSIVE ACOUSTICS

Within the context of monitoring MRE devices, passive acoustic monitoring (PAM) instruments have primarily been used to (1) characterize the soundscape of energetic marine environments (e.g., ambient sound and MRE device-associated noise; for details, see Chapter 4, Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices), and (2) monitor for echolocating marine mammals (e.g., detection and localization; for details, see Chapter 3, Collision Risk for Animals around Turbines). PAM of MRE devices is important because these devices may generate underwater noise (e.g., cavitation and motor/mechanical noise [Wang et al. 2007]) that could affect animal navigation, communication, predation, and life cycles (Lombardi 2016; Pine et al. 2012). Despite a growing body of PAM effort around MRE devices, no commercially available acoustic monitoring systems have been designed specifically for monitoring in the highly energetic marine environments that are sought for MRE extraction. Instead, various PAM technologies designed for more benign marine environments have been experimentally deployed in high-flow environments to assess their suitability for monitoring in these conditions. These technologies include conventional cabled or autonomous hydrophone and analog-to-digital instrument packages, internally recording hydrophones with digital interfaces, cabled and autonomous hydrophones or vector instrument arrays, and integrated hydrophone and data processing systems for marine mammal detection. In this section, we first consider the challenges faced by PAM in high-flow environments, and then provide an overview of the state of the science with respect to the use of PAM technologies for monitoring marine sound and marine mammals.

Challenges

A variety of factors (e.g., flow noise, natural ambient sound, instrument size and geometry, and deployment method) influence the detection efficiency of PAM instruments. However, the primary challenge for PAM in highly energetic marine environments is the identification and mitigation of flow noise (Bassett et al. 2014; Lombardi 2016; Thomson et al. 2012) generated by pressure fluctuations caused by turbulent flow on the surface of the hydrophone, or the noise made by water moving rapidly across the surface of the hydrophone. In energetic marine environments, flow noise can mask true propagating sound over a large bandwidth (i.e., 0–1 kHz), with increasing intensity and decreasing frequency, while sediment movement can generate noise in the 10s of kilohertz, depending on grain size and material (Bassett 2013; Raghukumar et al. 2019). This complicates the accurate characterization of ambient sound and the quantification of anthropogenic noise and reduces the effective detection range for echolocating marine mammals.

A suite of mechanical solutions to mitigate flow noise have been proposed. For instance, linear arrays of hydrophones have been used to reduce flow noise when monitoring tidal energy turbines in open channel turbulent flow (Auvinen and Barclay 2019; Worthington 2014). Because the flow noise is generated locally on each instrument, it is independent from one instrument to the next, but true propagating sound will appear to be coherent across the array. By coherently averaging the signals across the array, the flow noise may be suppressed while the true sound is amplified. Another commonly used option is the deployment of instrumentation on Lagrangian drifting floats in place of fixed moorings, and the use of flow shields, baffles, and vibration isolation mounts to minimize flow noise. However, none of these approaches are entirely effective at removing flow noise, and some options (e.g., flow shields) can degrade the detection of propagating sound if they are not designed appropriately.

Marine Sound Monitoring

Copping et al. (2013) and Robinson and Lepper (2013) provided comprehensive reviews of all published acoustic environmental monitoring activity for MRE devices up to 2013. Online supplementary Table S10.1 (online at: *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-environmental-monitoring*) provides an update and expansion of the two previously mentioned 2013 reports and summarizes the various PAM efforts used to characterize (1) ambient noise baseline measurements, (2) operational noise, (3) construction and installation associated noise, and (4) planned transmissions, and includes selected publications describing the results. Monitoring for marine noise around MRE sites should follow the protocol of the International Electrotechnical Commission Technical Specification (IEC TS) 62600-40:2019, which provides uniform methodologies for consistently characterizing the sound produced by the operation of marine energy converters that generate electricity from wave, current, and thermal energy conversion (IEC 2019; for details, see Chapter 4, Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices).

Marine noise at MRE sites has been characterized most often using a combination of drifting buoy or boat-based measurements; moored/bottom-mounted systems and directional arrays or paired hydrophones have been used less frequently. However, many of the early studies that used drifting boat-based measurements suffered from significant contamination of the acoustic recordings by noise generated by surface motion, including waves lapping against the boat hull and topside activity. Subsequent studies deployed hydrophones under floating buoys using isolation and suspension systems, drogues, or catenary sections to reduce noise contamination (Figure 10.1). These hydrophone deployments are described as having the highest fidelity relative to the true sound field—a claim that is frequently substantiated by the reduction of flow noise and motion-induced noise levels in subsequently collected datasets.

Operationally, moored/bottom-mounted systems provide the ability to monitor a single point in space for extended periods of time, whereas drifting systems measure a snapshot (typically on the order of minutes) of the noise field over a wider geographic area. There are advantages and disadvantages to each

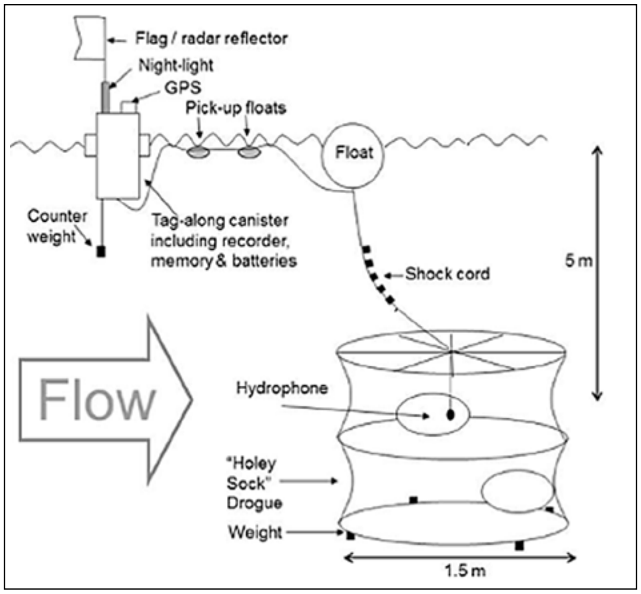

Figure 10.1. Schematic of the components of the "drifting ears" autonomous recording drifter specifically developed for use in tidal streams. This system was designed to keep the hydrophone in a fixed position relative to the body of moving water and is placed in a submerged underwater drogue. (From Wilson et al. 2014)

approach, depending on the context of the monitoring program being considered. For instance, for quantifying MRE device-generated noise, flow noise detected by a moored/bottom-mounted system typically masks the frequencies of interest (10s–100s of hertz), necessitating a labor-intensive and carefully executed drift-based measurement campaign. However, in the case of continuous real-time monitoring, a moored/bottom-mounted system is the only realistic option at this time, and methods of flow noise suppression (e.g., a flow shield) must be used if the objective includes quantifying MRE device-generated noise. However, there is no standard flow shield design available. Results from flow shield experiments have provided mixed results; some studies confirm a reduction in flow noise (Bassett 2013; Raghukumar et al. 2019), and others demonstrate a reduction in system sensitivity with no effect on flow noise in the band of interest (Malinka et al. 2015; Porskamp et al. 2015).

Digital hydrophones are widely available from a suite of manufacturers, are relatively compact in form, and are preferable for long-term deployments of moored/bottom-mounted observation systems because of their ability to transfer data at high speeds with little signal attenuation. The future automation of drifting PAM systems using unmanned aerial vehicles (UAVs) to take underwater noise measurements (Lloyd et al. 2017) may alleviate the laborious nature of previous drift-based monitoring campaigns, but these techniques are yet to be demonstrated. The use of a station-keeping autonomous hovercraft with a deployable acoustic instrument has also been proposed (Barclay 2019), and both of these technologies could provide duty-cycled long-term monitoring of MRE sites without interference from flow noise.

Marine Mammal Monitoring

A variety of PAM technologies are used for monitoring the presence of vocalizing marine mammals and their interactions with MRE devices. Most marine mammal monitoring programs that employ PAM technologies use porpoise and dolphin echolocation clicks to detect, classify, and localize the various species. These short-duration signals have reasonably wide bands (10–50 kHz) and are centered at relatively high frequencies (90–130 kHz). However, the detection efficiency of PAM instruments for monitoring marine mammals is affected by a variety of factors, including the vocalization bandwidth for the species being monitored and the potential masking of these sounds by flow noise and ambient noise (e.g., sediment transport on the seafloor), as well as by the propagation environment, reverberation, instrument placement, and instrument deployment methodology (Bassett et al. 2013; Porskamp et al. 2015; Tollit and Redden 2013). By understanding the relative effects of these factors, the performance of PAM technologies for monitoring marine mammals around MRE devices can be assessed. For instance, some frequently observed baleen whales in the Bay of Fundy, Nova Scotia, Canada, (e.g., humpback, fin, and minke whales) produce low-frequency sounds (below 1 kHz), and masking by flow and sediment transport noise may contribute to the absence of their detections using PAM technologies. In addition, a modeling exercise found that the passive acoustic detection range for southern resident killer whale (*Orcinus orca*) frequently observed in Admiralty Inlet, in Washington State, United States (U.S.) (Snohomish Public Utility District 2012), was reduced by 90 percent during flood and ebb tides suitable for turbine operation in a tidal channel because of flow noise (Bassett 2013).

Because the primary signal of interest for monitoring marine mammals around MRE devices is echolocation clicks, the data recording packages suitable for detection must have high sampling rates (>250 kHz) and large memory capacities for storing the raw pressure time series. The resulting data must then be processed for detection, classification, and localization using either commercially available software or custom-designed detection algorithms. A popular choice for this task is PAMGuard (Gillespie et al. 2008a) — an open-source software that automates detection and classification of sounds in the time series and permits localization. While "conventional" PAM instruments (Figure 10.2a) frequently require separate hardware (recording) and software (detection and classification) systems, alternative "stand-alone" instruments (Figure 10.2b) allow the pressure time series to be analyzed in real time (following some prescribed criteria for detection and classification), thereby permitting the raw data to be discarded while storing the associated metadata.

Figure 10.2. Examples of a "conventional" PAM instrument (Ocean Instruments NZ SoundTrap ST300 HF) (a) and a "stand-alone" PAM instrument (b). (Photos courtesy of Daniel Hasselman)

These two classes of PAM instruments (i.e., "conventional" and "stand-alone") have been deployed in drifting, moored, bottom-mounted, and MRE device-mounted configurations to detect, classify, and localize various echolocating marine mammals, but have been shown to have different performance depending on a variety of factors, including the metric being assessed. For instance, a study in the Baltic Sea found that a stand-alone instrument detected 21 to 94 percent of the click trains detected by PAMGuard when applied to the recordings made with a co-located conventional instrument (Sarnocinska et al. 2016). The reduced rate of detections (i.e., clicks per minute) was due to several factors, but primarily the fact that PAMGuard detected individual clicks, whereas the proprietary software on the stand-alone instrument detected click trains. However, data collected as clicks per minute by conventional and stand-alone PAM instruments cannot be directly compared, because there is large spread in the detection ratio of these systems and no consistent linear relationship between the detection rates for these instruments (Sarnocinska et al. 2016). Alternative metrics such as "detection positive minutes per unit time" (Roberts and Read 2015) and "echolocation clicks per hour" (Jacobson et al. 2017) have revealed greater agreement (i.e., higher accuracy and lower spread in detection ratio) between classes of PAM instruments. However, prior studies have shown that co-located conventional instruments record five to ten times more detection minutes per day than stand-alone instruments (Adams 2018; Porskamp et al. 2015; Tollit and Redden 2013), and the differences are attributed to the detection algorithm employed and the greater impact of flow-induced noise (i.e., sediment transport) when using stand-alone instruments.

One concern with the use of stand-alone PAM instruments in high-flow environments centers around the issue of "lost time" (or time when the system is not operational) and the potential for under-reported click trains. Flow-induced noise can cause the maximum number of recordable clicks per minute to be exceeded on a stand-alone instrument, resulting in saturation of the detection buffer, and generating lost time (Tollit and Redden 2013). Comparative studies in high-flow environments have shown the effect of lost time from flow-induced noise for bottom-mounted and moored stand-alone instruments (Porskamp et al. 2015; Wilson et al. 2013). Bottom-mounted stand-alone instruments generally have more detection minutes per day than moored systems, during which noise generated by the mooring system being "blown down" against the seabed during periods of high flow may have saturated the detection buffer of the instrument (Porskamp et al. 2015). Alternatively, drifting stand-alone instruments suspended from Lagrangian drogues or floats do not appear to suffer from lost time, suggesting that flow-induced noise has less of an impact on the detection buffer in this configuration (Adams 2018; Benjamins et al. 2016; Wilson et al. 2013).

Detection efficiency also differs between PAM technologies; conventional instruments generally have greater detection ranges (0–500 m) than stand-alone instruments (0–300 m), depending on the conditions under which the tests are conducted (Benjamins et al. 2017;

Kyhn et al. 2008, 2012; Polagye et al. 2012; Porskamp et al. 2015; Roberts and Read 2015; Tollit and Redden 2013).

Three three-dimensional (3D) localization studies have been conducted to date. The first involved a vertical array of eight large-aperture hydrophones combined with a small quad array. This system was deployed from a drifting ship to localize echolocating marine mammals, and provided a detection range of 200 m (Macaulay et al. 2017). The second study involved a 3D distribution of seven hydrophones mounted on a tidal turbine in Ramsey Sound, Wales, and was used to detect and localize dolphins and porpoises (Malinka et al. 2018). The estimated detection range of this system was 20 to 200 m for sound sources with source levels of 178 to 208 dB re 1 µPa, respectively. However, there was an estimated 50 percent probability of detection and localization for ranges >20 m, and only an estimated 10 percent probability at 50 m. The third study involved a PAM array for the commissioning of a tidal kite in the Holyhead Deep, Wales, to detect porpoises and dolphins. It was composed of an 8-channel system containing two clusters of four hydrophones that would together localise cetacean echolocation clicks in 3D and monitor near-field movement and evasion around the kite. A second array of six single channel SoundTraps (Ocean Instruments) surrounded the kite to detect mid-field activity that may inform avoidance. Recorders for the 8-channel array included long-endurance batteries and 4 TB of removable data storage which resulted in a predicted recording duration of approximately 56d while sampling at 312 kHz.

Although conventional PAM instruments record the entire pressure time series and provide advantages over stand-alone systems for the detection, classification, and localization of echolocating marine mammals in high-flow environments, important factors to consider when pairing PAM technology with monitoring objectives are the deployment configuration and associated costs. While signal masking by flow noise, sediment noise, and mooring noise can limit the utility of moored or bottom-mounted PAM instruments, PAM instruments suspended below floats or drogues limit flow noise. Although deploying floating PAM instruments requires a large field effort upfront, data collection can occur over a protracted timeframe (days) to reduce overall costs. The development of flow noise reduction strategies could aid marine mammal monitoring with PAM instruments from bottom-mounted systems and reduce the confounding effects of noise in high-flow environments.

10.2.2. ACTIVE ACOUSTICS – IMAGING SONARS

Active acoustics, as opposed to passive acoustics, generate a sound that is received as a return from the object of interest. For environmental monitoring at MRE sites, imaging sonars provide the advantage of high-resolution imagery in turbid waters without the need for artificial illumination (Hastie et al. 2019b). Although imaging sonars have several advantages over optical imagery, classification of targets is generally more difficult, and data processing methods to allow real-time target detection, tracking, and classification relative to current flows are currently under development. Because the environmental conditions and instrument configurations vary among monitoring projects, target-detection algorithms require “tuning” relative to current flow, and the final target classification step generally requires information from a secondary instrument, such as an optical camera, an echosounder, or an acoustic Doppler current profiler (ADCP), for validation.

There are currently more than a dozen commercially available imaging sonars that have been developed for use in high-energy marine environments (each differing in functional range, resolution, field of view, and mechanical configuration), but the typical application is for underwater vehicle navigation and situational awareness. Further, not all imaging sonars have been designed for long-term deployments without regular maintenance. Most uses do not require the sonar control software to be integrated on a multi-instrument platform with other active acoustics. Thus, many of the commercially available imaging sonars are not well suited for monitoring MRE devices, but several have been demonstrated on previous projects. This section provides an overview of the most frequently used and commercially available imaging sonars for monitoring MRE devices.

The use of imaging sonars for environmental monitoring in high-flow environments has been documented in approximately 20 journal publications and project reports, and is spread across a range of applications that may be categorized by deployment type (i.e., downward looking from a surface vessel, mounted on a subsea platform, or integrated into turbine substructure), deployment duration (i.e., from less than one day to several months), target monitoring goals (i.e., as defined by regulatory requirements, or project developer's interest in retiring perceived risks), and method of data acquisition (i.e., often continuous collection) and processing (i.e., a combination of manual review and automated approaches). Given that every monitoring project has distinct requirements, which may change over the course of the project, the most appropriate sonar for each application will also vary. The technical specifications for different sonars affect their suitability for monitoring MRE devices. The specifications that have the greatest impact on the capabilities of imaging sonars for monitoring include (1) the operating frequency, (2) the field of view or swath angles, (3) the functional range, (4) the input/output (I/O) trigger option, and (5) the software development kit (SDK). In general, the sonar functional range is determined by the operational frequency, while the field of view and resolution are functions of the number of beams. The option for an input trigger or SDK is crucial for integration on a multi-instrument platform. A summary of the technical specifications for the six most common imaging sonars used for monitoring MRE devices and examples of specific applications are provided in online supplementary Table S10.2 (online at: https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-environmental-monitoring).

Applications

Imaging sonars have been used in a variety of configurations and applications relevant to monitoring MRE devices (Hastie et al. 2019a, 2019b). Several studies have mounted imaging sonars on a pole and deployed the sonar over the side of a vessel to conduct mobile surveys (Grippo et al. 2017; Melvin and Cochrane 2015; ORPC Maine 2014; Parsons et al. 2014, 2017). Parsons et al. (2017) conducted a vessel survey using a Tritech Gemini and used the native software for data collection and processing. The sonar configuration and vertical field of view (Figure 10.3) and sample data from Parsons et al. (2014, 2017) (Figure 10.4) are provided below. While the relatively short duration of vessel surveys and the constantly changing field of view complicate background subtraction for automated data processing, vessel surveys can cover large areas and the motion of the sonar can be used for 3D reconstruction. Further, the relatively short duration of deployments simplifies sonar maintenance and allows for continuous data collection; eliminating the need for real-time target-detection and -tracking algorithms. When vessel surveys with imaging sonars are conducted in conjunction with fisheries echosounders, the combination of techniques allows for fish classification (echosounders) and tracking (imaging sonars) when targets can be co-registered between the data streams.

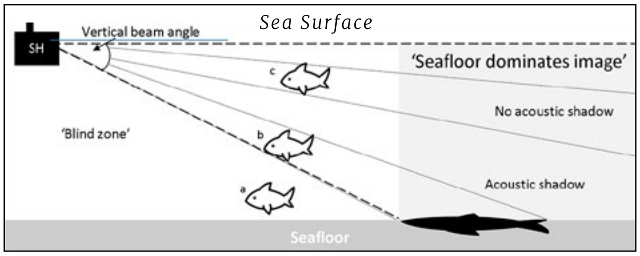

Figure 10.3. Example of a vessel-based sonar configuration. (From Parsons et al. 2017)

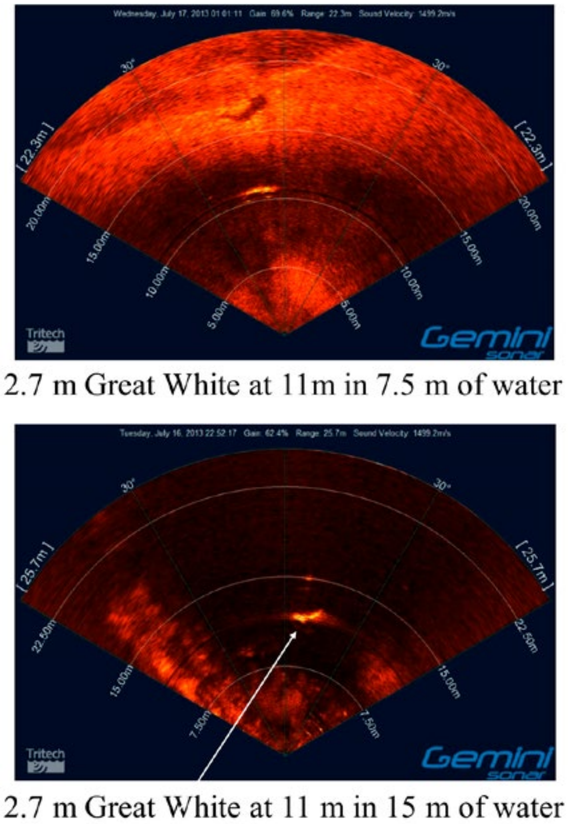

Figure 10.4. Example data from a vessel-based survey using Tritech Gemini. (From Parsons et al. 2014)

Imaging sonars have also been integrated into a variety of subsea platforms that have been deployed near MRE devices. The Flow, Water Column and Benthic Ecology (FLOWBEC)-4D platform (Section 10.4.3) integrates an Imagenex 837B Delta T imaging sonar with a suite of instruments and a large battery bank to facilitate con-

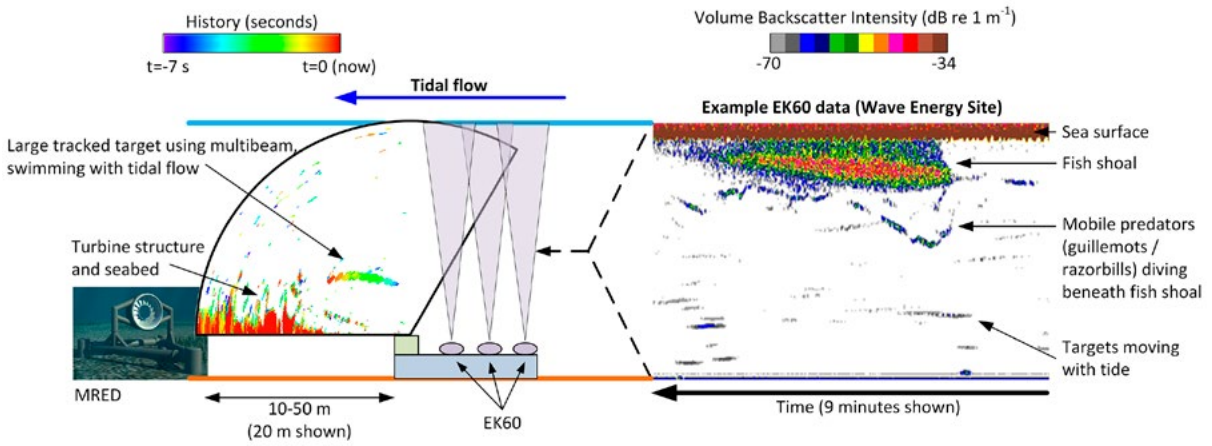

Figure 10.5. Example data from the Flow, Water Column, and Benthic Ecology (FLOWBEC)-4D deployment at the European Marine Energy Centre. (From Williamson et al. 2016a)

tinuous data collection during two-week autonomous deployments. The Imagenex 837B Delta T sonar was chosen for this platform because of previous experience with the instrument and its relatively low cost, low power consumption, and low data bandwidth. Experience with this sonar simplified integration with the platform and synchronization with a Simrad EK60 echosounder, and the low power consumption and low bandwidth requirements made this imaging sonar better suited for autonomous deployments. The sonar is mounted on the FLOWBEC-4D platform so that the field of view allows for target co-registration with the echosounder and tracking capabilities. Although the narrow beam angle for both the imaging sonar and the echosounder results in only a narrow horizontal region being monitored concurrently, deployments to date have facilitated the development of target-detection and -tracking algorithms to simplify data post-processing. Figure 10.5 provides an example of a processed data sequence with the imaging sonar and echosounder tracking biological targets on their approach to a turbine structure.

The Adaptable Monitoring Package (AMP) (Section 10.4.1) is an integrated instrumentation platform developed by the University of Washington for monitoring tidal energy devices (Cotter et al. 2017, Polagye et al. 2020), but it has also been used for monitoring at wave energy test sites, although without WECs (i.e., PacWave site in Oregon, U.S., and Wave Energy Test Site [WETS] in Hawaii, U.S.). Imaging sonars that have higher frequencies have shorter ranges, while lower frequencies extend the range of target detection. While an earlier version of the AMP included a Kongsberg M3 imaging sonar (Cotter et al. 2017), subsequent generations of the platform have included a Tritech Gemini and a Teledyne BlueView imaging sonar to take advantage of the long and short relative ranges of these instruments. Because of the high bandwidth of the instruments on the AMP, imaging sonar data are processed in real time to detect targets and trigger the optical camera lights and data-archiving process. This approach avoids data mortgages (Section 10.3.2) and simplifies any post-processing steps required.

Beyond their inclusion on integrated monitoring platforms, imaging sonars have also been deployed as stand-alone instruments. For instance, a Sound Metrics Dual-Frequency Identification Sonar (DIDSON) imaging sonar was deployed on a cabled platform approximately 12 m from the base of the tidal turbine used for the Verdant Roosevelt Island Tidal Energy project (Bevelhimer et al. 2016). The platform was equipped with a pan-and-tilt system to allow dynamic positioning of the sonar so that the field of view could be adjusted as required. The monitoring objective of the sonar was to observe fish behavior relative to the turbine and look for evidence of avoidance. Although the turbine failed soon after its deployment, the sonar collected data continuously for 19 days.

Imaging sonars have also been mounted directly on turbine structures for monitoring purposes. The SeaGen project in Strangford Lough used imaging sonars for monitoring the interactions of marine mammals with tidal energy turbines for the greatest length of time. This project used the Tritech Gemini imaging sonar for monitoring harbor porpoises (*Phocoena phocoena*) and harbor seals (*Phoca vitulina*) (Hastie 2013), and allowed Tritech International Ltd. to implement autonomous real-time target detection and tracking in their software. Two Sound Metrics DIDSON imaging sonars were mounted on the Ocean Renewable Power Company (ORPC) vessel-based turbine test platform deployed in Cobscook Bay, Maine, U.S., in 2012 to monitor fish (Viehman and Zydlewski 2014). Data were collected continuously for 22 hours and included manual post-processing. Although these sonars have the highest resolution of all commercially available imaging sonars, they have a short range and narrow field of view.

Key Considerations

The successful use of imaging sonars and their integration with multi-instrument platforms for monitoring MRE devices will depend on a variety of factors (i.e., mounting and orientation, electrical and communication connections, software for instrument control and data acquisition, and software for data processing). Here, we provide an overview of some of these key considerations.

The ideal orientation for an imaging sonar depends on the location and size of the MRE device and the monitoring objectives. The sonar swath may be oriented to look across, in front of, or behind a device, with a vertical or horizontal orientation, and either from a bottom or surface platform. Each of these configurations has its own challenges and benefits that are difficult to predict prior to testing. If the monitoring objective includes individual fish passage, then a high-resolution sonar will need to be deployed close to (or mounted on) the MRE device. If the monitoring objective is to cover the full area of an MRE device, then the deployment of one (or more) sonars with suitable range and resolution may need to be deployed on a cabled or autonomous subsea platform.

Custom software for controlling the imaging sonar and acquiring data are provided by instrument manufacturers. Customization beyond the native software capabilities is required for integration of multiple instruments into monitoring platforms, and when data are processed in real time or acquired on a duty cycle. For these reasons, sonars with manufacturer-supported SDKs are more suitable for platform integration. For instance, instrument control and data acquisition software for the AMP was developed using National Instruments LabView for both the Teledyne BlueView and Tritech Gemini imaging sonars.

Lessons Learned

Many of the key considerations for the successful use of imaging sonars and their integration with multi-instrument platforms come from previous failures that often remain undocumented by the teams who have deployed them. The most common challenges stem from the durability of the imaging sonar for lengthy deployments, or from the software for data collection and processing.

Long-term deployments of instruments in the marine environment will result in biofouling that can inhibit data collection (see Chapter 6, Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices). Although biofouling of an imaging sonar's transducer does not always degrade the imagery, it can damage sensitive components over time. While instituting a regular maintenance schedule that prevents the biofouling of sensitive components from becoming established is the best solution, it may not always be possible. Alternatives for sensitive components include using biofouling wipers (e.g., ZibraTech Inc.) for optical view ports, ultraviolet lights, antifouling paint, or highly concentrated zinc oxide paste (exception: stainless-steel surfaces). For less sensitive components, copper or vinyl tape may be used to coat surfaces to inhibit growth or easily remove biofouling.

The integration of imaging sonars on multi-instrument platforms can reveal interference with other active acoustic sources and electrical noise. For instance, thin radial lines appeared on the BlueView imaging sonar when strobe lights for an optical camera on the AMP were activated (Figure 10.6). This kind of interference is typically due to direct current (DC) power converters that operate at frequencies similar to the imaging sonar and produce noise in the sonar imagery. This can be remedied by isolating and filtering the power supplied to the imag-

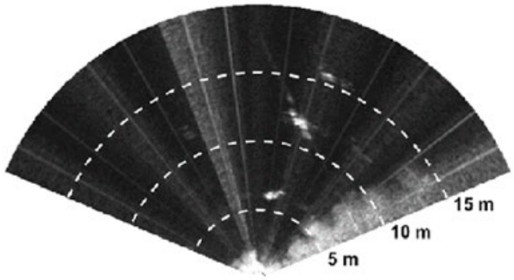

Figure 10.6. Example of electrical interference in data from a BlueView imaging sonar on the Adaptable Monitoring Package (AMP). Thin radial lines are observed when strobe lights for optical cameras are active. (From Joslin 2019)

ing sonar. To avoid "cross-talk" between active acoustic instruments, synchronization of instrument controls is necessary to interweave pings, and doing so typically requires the imaging sonar to have an input trigger option that can be synched with a central controller.

The presence of non-biological targets (e.g., debris) and environmental artifacts (e.g., turbulent vortices, entrained air in the water column) that typify MRE sites presents challenges for environmental monitoring, because these conditions can mask actual targets of interest and impede automatic target-detection algorithms. Similarly, moving targets in the sonar field of view (e.g., turbine blades, water surface) or a sonar mounted on a moving platform can result in large changing acoustic artifacts in the sonar image (Urban et al. 2017). For these reasons, integration of imaging sonars mounted on subsea platforms, and deployed to the side of MRE devices, are most likely to yield the highest quality sonar imagery.

Another consideration for use of imaging sonars for monitoring is the response of marine animals to the noise produced by the sonar. While the operating frequencies of most imaging sonars are well above the hearing levels of marine mammals, they can produce sound at lower frequencies, and it is possible that marine animal behavior may be affected (Cotter et al. 2019; Hastie 2013). Although the sound levels are not high enough to be of concern, additional research is needed to fully characterize behavioral changes that are detected by imaging sonars (and echosounders).

10.2.3. ACTIVE ACOUSTICS – ECHOSOUNDERS

High-fidelity echosounders are a standard tool in fisheries science and are routinely used to quantify fish abundance and distribution (Simmonds and MacLennan 2007). They are also valuable for monitoring the interactions of fish with MRE devices and have been used in a variety of configurations, including mobile hydroacoustic surveys (McGarry and Zydlewski 2019; Melvin and Cochrane 2014, 2015) and stationary deployments both at the sea surface (Viehman et al. 2015) and on the seabed (Viehman and Zydlewski 2017; Viehman et al. 2017; Williamson et al. 2016a).

The suite of scientific echosounders that are commercially available can be categorized by (1) those that have been used and found to be effective by the scientific community, (2) those that can be calibrated, and (3) those that have digital output; these echosounders constitute instruments that have the desired features for quantitative monitoring (Demer et al. 2017; Horne 2019). These characteristics combined with packaging flexibility, transmission pulse types, and processing software options, all vetted by the international community, make the current generation of commercial scientific echosounders the instruments of choice for monitoring fish at MRE sites (Horne 2019). Some manufacturers also offer a line of scientific echosounders that have common architecture and design features, and include a series of instruments that can actively transmit in narrowband, single-frequency, continuous wave or wide-bandwidth, frequency-modulated mode. When equipped with split-beam transducers, individual targets can be tracked, and their scattering strength compensated for based on their location in the beam. These echosounders can be used in traditional vessel deployments for mobile surveys, with transducers mounted on the hull of a ship, on a pole, or in a towbody, deployed autonomously on moorings and subsea platforms, integrated into autonomous or cabled subsea monitoring packages, or used on remotely operated underwater vehicles (ROVs) and autonomous underwater vehicles with an external power supply.

Challenges and Mitigation Techniques

The primary challenge for using scientific echosounders to monitor fish interactions with MRE devices in high-flow environments is acoustic signal scattering from air entrained in the water column — a physical feature common to MRE sites. Because sound energy emitted from a transducer will be reflected when the acoustic impedance (product of sound speed and density) differs from the surrounding water, scattering from entrained air affects the ability to detect targets of interest and subsequently discriminate between the targets that are biological and those that are non-biological. In addition, when volume scattering from physical sources such as bubbles is sufficiently high, the presence of biological and other non-biological targets of interest can be masked (Figure 10.7).

Generally, the probability of detecting a target can be maximized by a combination of (1) increasing the source level (i.e., power of the signal emitted from the transducer), (2) reducing the range to targets, (3) matching the transmit frequency to the intended target

(Simmonds and MacLennan 2005), (4) increasing the signal-to-noise ratio (e.g., using matched filter and pulse compression techniques for broadband echosounders [Ehrenberg and Torkelson 2000; Chu and Stanton 1998] or increasing the pulse length for narrow band), and (5) processing raw data to remove noise. While these techniques can improve the detection of targets that have weak scattering properties, or targets at such great distance from the transducer that the returned echo is not sufficiently greater than the level of the background ambient noise present in the sea, other techniques are required to classify echo returns from the targets of interest (fish) and the returns from other unwanted targets in the water column (bubbles).

The challenge of the presence of bubbles in the water column fundamentally complicates the interpretation of hydroacoustic data. Hydroacoustic methods work well when the medium (seawater) is fairly uniform, but they can be severely challenged at MRE sites in the presence of the confounding or masking factor of air bubbles (Melvin and Cochrane 2015; Trevorrow 2003; Vagle and Farmer 1992). The ability to discriminate between targets depends on a combination of factors. The most important are the scattering intensity and the frequency response. Bubbles, turbulent microstructure (if present), suspended sediments, zooplankton, and fish have scattering spectra that can be modeled and used to distinguish between them. However, it can be difficult to distinguish bubbles and fish, based on the frequency content alone, because they have similar spectra. If the bubble field is sufficiently large and the backscatter sufficiently strong, the backscatter from biological targets within the bubble field will be indistinguishable from the bubble backscatter.

Work has been ongoing to develop methodologies for reducing the ambiguity in the classification of acoustic signal scatterers, whether among species or size classes (De Robertis et al. 2010; Horne 2000; Korneliussen 2018), or distinguishing biological sound scatterers (fish, zooplankton) from physical sources of scattering (entrained air, microstructure) (Lavery et al. 2007, 2010; Ross and Lueck 2003; Warren and Wiebe 2008). The echo amplitude of energy backscattered from biological and physical sources is a complex, frequency-dependent function of the material properties (e.g., gas [bubbles] or gas-inclusions [swim bladders], fluid-like, or hard parts [bony skeleton or shell]), shape, and orientation; a complete list is available in Table 4.1 of Korneliussen (2018). Exploiting the frequency-dependent response of scatterers has the potential to reduce ambiguities in the interpretation of scattering data. To that end, instrumentation and techniques have been under development for collecting and interpreting backscattering data across a wide band of frequencies, whether the acoustic signal consists of a single continuous band (i.e., broadband), multiple broadband signals, multiple narrow bandwidth signals, or a combination of broadband and narrowband signals (Bassett et al. 2018; Jech et al. 2017; Stanton et al. 2012).

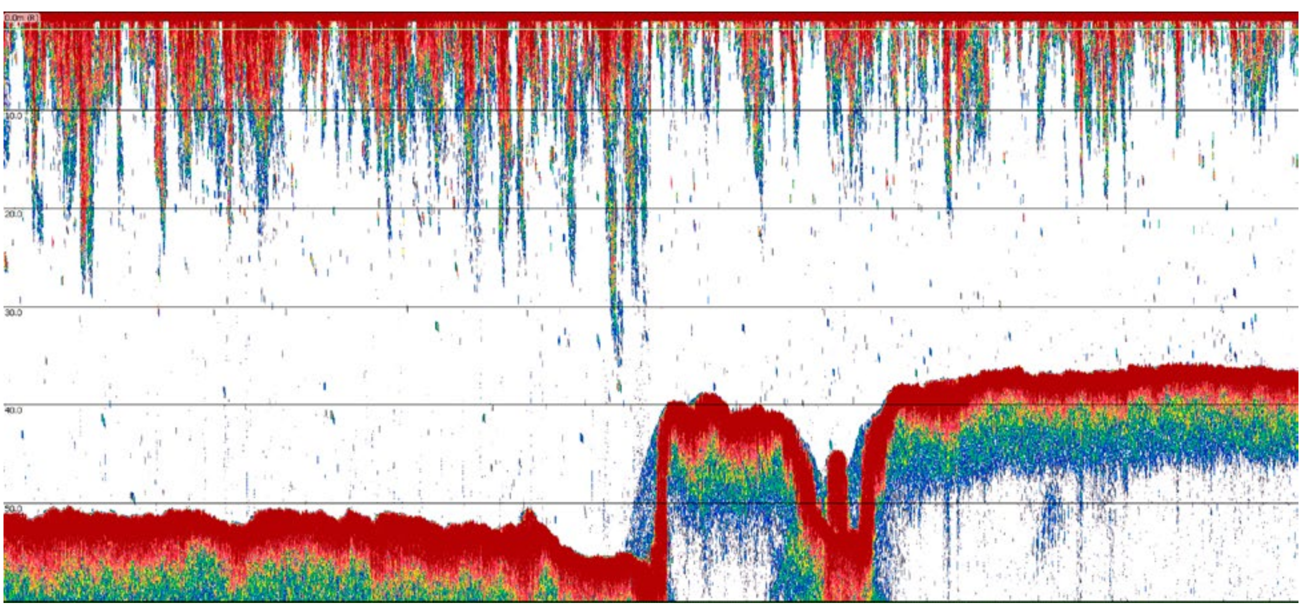

Figure 10.7. Echogram from a single transect during a mobile hydroacoustic survey in Minas Passage, Nova Scotia, Canada, showing the extent and variability of air entrainment during peak flow conditions. (Image courtesy of FORCE)

However, acoustically distinguishing swim-bladdered fish from air bubbles is an ongoing area of research because of the similarity in echo amplitudes caused by the presence of gas in both (Melvin and Cochrane 2015). With continued development of commercially available software packages (e.g., Echoview, ESP3, LSSS, Macheto, SonarX), a variety of filtering techniques are available for removing unwanted targets. A diversity of techniques have been developed to remove noise (De Robertis and Higginbottom 2007; Korneliussen 2000) and isolate target groups (De Robertis et al. 2010; Fernandes 2009; Kloser et al. 2002; Sato et al. 2015). To address the analytical challenges that arise when the background acoustic characteristics are extremely variable, multifrequency methodologies capable of target detection within some of the challenging conditions at MRE sites have been developed. They include the application of a bitmap to isolate targets of interest from backscatter data and automating the use of multifrequency acoustic data to delineate turbulent regions and then extract biological targets from within those regions (Fraser et al. 2017a; Williamson et al. 2017).

Applications

Although scientific echosounders have been mounted on vessels and used for mobile hydroacoustic surveys around MRE sites (McGarry and Zydlewski 2019; Melvin and Cochrane 2014, 2015; Shen et al. 2016), these surveys are subject to a suite of inherent challenges associated with strong currents and turbulent water that affect their efficacy (e.g., vessel control and positioning, ship noise, intermittent signal loss, and the influence of surface conditions on the extent of entrained air in the water column) (Melvin and Cochrane 2015). Nonetheless, this approach is valuable for generating metrics of fish density from the acoustic backscatter of fish in the water column and understanding fish distribution near MRE devices (Staines et al. 2019). An alternative configuration for monitoring MRE devices is stationary deployment of echosounders—both on the surface (Viehman et al. 2015), and on the seabed (Fraser et al. 2018; Viehman et al. 2017; Viehman & Zydlewski 2017; Williamson et al. 2016b). The advantage of a stationary deployment is the potential for persistent monitoring throughout the duration of the deployment. This approach is useful for generating long-term, high-resolution sampling for understanding biological processes at MRE sites where large changes may occur over multiple, wide-ranging time scales (Viehman & Zydlewski 2017). However, observations from stationary deployments are spatially limited as a set of point measurements, and understanding how to set interpolation distances between replicated stationary instruments (e.g., representative range) is important for collecting meaningful spatiotemporal data across equivalent spatial and temporal scales (Horne and Jacques 2018).

A downward-looking single-beam Simrad ES60 echosounder (operating at 38 and 200 kHz simultaneously) was deployed from the side of a moored vessel and used to characterize patterns of fish presence and distribution at the ORPC tidal energy site in Cobscook Bay, Maine, U.S. (Shen et al. 2016; Staines et al. 2019; Viehman et al. 2015). The density of fish was found to vary seasonally; the greatest densities were observed in the spring and late fall (consistent with migratory periods), and the greatest densities were consistently detected near the sea floor (Viehman et al. 2015). These stationary data were combined with mobile survey data collected at the ORPC site using a Simrad EK60 split-beam echosounder to understand fish behavior around MRE devices and generate an encounter probability model (Shen et al. 2016). The study suggested that fish can avoid tidal turbines from 140 m away, and the encounter probability varied depending on month, diel condition, and tidal stage (Shen et al. 2016).

Viehman and Zydlewski (2017) examined data collected by a bottom-mounted, horizontally oriented Simard EK60 split-beam echosounder deployed near a tidal energy turbine (TidGen® Power System) at the ORPC site in Cobscook Bay. Two years of continuously collected data were used to characterize patterns in fish presence at the tidal energy site, and revealed that the abundance of fish near the device varied greatly with tidal and diel cycles in a seasonally changing relationship that was likely linked to the seasonally changing fish community in the region. Contrary to observations at other tidal energy sites, the number of fish detected was not associated with current speed and did not decline with increasing current speed (Viehman and Zydlewski 2017).

An upward-facing ASL Environmental Sciences Acoustic Zooplankton and Fish Profiler (AZFP) with a single-beam transducer was mounted on a subsea platform (FAST-1) and deployed at the Fundy Ocean Research Center for Energy (FORCE) test site in Nova Scotia, Canada, to characterize the density and distribution of fish prior to the deployment of the Cape Sharp Tidal

Venture (OpenHydro) open-center tidal turbine in 2016 (Viehman et al. 2017). This study found that fish density was higher and less variable in winter than in summer (likely due to the presence of migratory vs. overwintering fish), and that fish vertical distribution varied with the sample period, diel stage, and tidal stage (Viehman et al. 2017).

Multifrequency data (38, 120, and 200 kHz) were collected using an upward-facing Simrad EK60 scientific echosounder mounted on the FLOWBEC platform (see Section 10.4.3) and deployed at the European Marine Energy Centre (EMEC) on multiple occasions (Williamson et al. 2016a, 2019; Fraser et al. 2018). Hydroacoustic data were processed using an adaptive processing method (Fraser et al. 2017a) and demonstrated that fish were attracted to a bottom-mounted tidal turbine and its support structure (Williamson et al. 2019). The study also revealed that aggregation and vertical distribution of fish in the modified flow conditions of the turbine was dependent on tidal and diel phase, and provided evidence of some avoidance of turbine depth range during peak flow (Fraser et al. 2018).

10.2.4. VIDEO CAMERAS

Video cameras (VCs) can be used to monitor marine animals' distribution and behavior, and determine the species and size of individuals (Box 10.1). Use of VCs is often needed to assess marine mammal, fish, and diving bird observations as they approach turbine systems; record blade interactions; determine species affected; or to assess the operation of the turbine system. Equipment configurations include single, multiple, or paired stereo cameras; paired lasers for measurement reference; artificial lighting; and autonomous, stationary or traversing data collection platforms. Remotely controlled positioners (pan and tilt) can be incorporated to aid in the collection of data.

VC systems are an important tool for collecting data at all MRE locations. VCs have the ability to document animal behavior and animal interactions with various man-made structures and their natural environment (Booth and Beretta 2002; Mueller et al. 2006). Providing high-resolution imagery that is easily recognizable to a human viewer is advantageous for interpreting and processing data. Even with an easily recognized format, data quality can be a challenge for the measurement objectives (e.g., counting and/or speciating animals, behavior classification, interactions with underwater objects). Numerous parameters (e.g., lighting, frame rate, instrument resolution, field of view) must be considered when using VC to observe animals underwater. The objectives of the VC application must be planned to assure that the observation or measurement goal is achieved. VCs are often used to validate objects and marine life when used in conjunction with active acoustics. Examples include validation of fish species during acoustic surveys using an ROV (Campanella and Taylor 2016).

Numerous vendors specialize in and provide commercial off-the-shelf (COTS) VC systems for research and still imagery, the majority of which are tailored for ROV applications. A wide range of options are available from low resolution (300 to 400 lines of horizontal resolution) to ultra-high resolution (2000 lines of horizontal resolution). Recording resolution is variable and typically consists of 4K, ultra-high definition, 720, 960, and 1080 pixels with variable frame rates. The price can range from inexpensive action VCs (<$1000; Struthers et al. 2015) to very expensive 4K ultra-high definition cameras in high-pressure–rated housings (>$4000). An overview of standard types of optical cameras is provided in online supplementary Table S10.3 (online at: *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-environmental-monitoring*).

Wide-angle field-of-view cameras are best suited for mounting close to structures to capture the largest viewing region. The field of view is mostly controlled by the choice of lens for the VC, specifically the focal length (the shorter the focal length, the wider the field of view). The camera lens size is dependent on the type of survey to be conducted. A wide-angle (2 to 3 mm) lens can be used for fish detection close to the camera, and a 5 to 8 mm fixed or zoom lens is often used for imaging objects at greater distances.

Monochrome VCs (Figure 10.8) are best suited for operating under low-light conditions and accrue smaller data files than color video. In certain conditions, color cameras can be used to help distinguish species. Some systems, such as Sony® Super HAD CCD imagers, support automatically switching to monochrome under low-light conditions, have auto white-balance, or allow users to manually adjust the images.

Figure 10.8. Example of a school of broad whitefish (*Coregonus nasus*) captured with a monochrome video camera. (Photo courtesy of Robert Mueller)

Many VCs are rated for minimum scene illumination, also known as the lux value; the lower the specified lux value, the less light is required to obtain optimal images. Dynamic range is a measure of the difference between the brightest and darkest values an instrument can resolve. High dynamic range is useful for low-light imaging. If a high dynamic range is present, then a higher quality large sensor digital single-lens reflex camera with 10 or more F-stops or raw images produced from the camera in video mode will produce better quality images.

Most commercial-grade cameras are depth rated and are in a waterproof housing made of titanium, Delrin, polyvinyl chloride, acrylic, or aluminum. An alternative to purchasing a camera already in a waterproof housing is to purchase a COTS camera and place it in a housing. The benefits of doing so include the ability to select from a variety of cameras, which often have variable recording rates, variable lens configurations and imagers, and variable control over image acquisition. One drawback is the additional connection cables needed to interface with the wet bulkhead connectors on the outside of the housing. Camera housings are generally pressure-tested to between 60 and 100 m, more available, and less expensive, while marine-grade underwater cameras placed in titanium or stainless-steel housings are more costly and rated to much deeper depths.

Applications

Systems to Measure Object Size and Swimming Speed

Fish size and swimming speed can be determined using stereo-VC systems. This method incorporates two cameras positioned side by side at a set distance. Images are synchronized via computer by using a LED light placed at a set distance and activated on/off and seen on both images (Harvey et al. 2002; Langlois et al. 2012; Lines et al. 2001; Trudel and Boisclair 1996), or by using a narrow-beamed strobe light (Williams et al. 2014). When objects move through both cameras' fields of view, locations in 3D space as well as object sizes can be determined. Camera spacing varies for each application. The stereo camera calibrations may provide in situ challenges in high-energy locations. Images can also be synchronized by hardware triggering of each camera using specialized software. Performing calibrations in a laboratory setting is easier, but the transfer of the cameras and mounting apparatus to the field site can be challenging because the cameras must remain in the same positions they were in during calibration. In the field, real-time tilt instruments can be attached to the cameras to assure they stay at the predetermined location. A recent application had 0.8 m spacing with a maximum range of a 5 to 6 m wide horizontal field of view (Hammar et al. 2013). In another study, camera spacing was 1.4 m, which was used to image objects at 2 to 10 m from the cameras depending on visibility, and it was more accurate when objects were less than 50° from the central axis of the cameras (Harvey and Shortis 1995, 1998). These systems can be effective at determining interactions with turbine blades, species composition, swimming speeds of fish, fish size, and distance of fish to blade interactions, and at estimating the speeds of currents (Harvey et al. 2002).

As an alternative to the use of paired cameras, paired parallel-mounted lasers can be incorporated with a single camera to determine object sizes. These systems are commonly incorporated for use on ROVs. Lasers are mounted on specialized brackets, which hold them parallel to each other so that the laser dot separation is consistent with the variable range to objects. The lasers shine onto animals, substrate, or other structures and allow for the scaling of these objects during later analysis. After VC images are taken in conjunction with the lasers, the size of the animals and other objects can be determined using imaging software. This system is somewhat limiting in that measurements can only be made when lasers appear on the object in contrast to stereo imaging where more objects can be measured per image.

Systems for Long-Term Recording and Storage

For long-term continuous recording, cabled systems of various types with a dedicated recording location on the shore or on a stationary platform have several advantages (online supplementary Table S10.4; online at: *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-environmental-monitoring*).

BOX 10.1

EXAMPLES OF MARINE RENEWABLE ENERGY (MRE) MONITORING USING SUBSEA VIDEO CAMERAS

Nova Innovation, Bluemull Sound, Shetland, Scotland (United Kingdom [UK]) – At the 30 kW demonstrator turbine installed by Nova Innovation in Bluemull Sound, subsea video is used to monitor for potential collisions and nearfield interactions of marine mammals with turbines (Smith and Simpson 2018). The video monitoring uses three cameras per turbine, attached to the nacelle (two directed toward the turbine rotor and one directed toward the seabed). The turbine is not illuminated, so video monitoring is only effective during daylight hours. The camera is connected to a standard closed-circuit television (CCTV) system with a motion trigger to record continuously, and triggered footage is retained for post-hoc analysis.

Sustainable Marine Energy, Grand Passage, Bay of Fundy, Nova Scotia (Canada) – At the PLAT-I tidal energy converter in Grand Passage, Nova Scotia, Canada, four MacArtney LUXUS Compact PUR subsea cameras were installed to collect underwater video to meet requirements under the Environmental Effects Monitoring Plan developed by Sustainable Marine Energy (Canada) Ltd. Each camera was positioned facing downstream, approximately centered on its associated rotor with a field of view approximately 10 percent larger than the rotor diameter. Visibility was generally good, featuring sufficient light and limited suspended particles. A total of 14 hours of video were reviewed by an experienced third-party contractor to screen for potential animal sightings. The video quality was rated as fair to good, and inanimate materials such as seaweed and other debris were noted frequently. Aside from several observations of jellyfish, only one positive identification of marine life was made (a small fish, possibly a rainbow smelt [*Osmerus mordax*]).

Ocean Renewable Power Company, Kvichak River, Iguigig, Alaska (United States [U.S.]) – In the Kvichak River, Alaska, optical cameras were used to understand fish behavior around a horizontal axis helical turbine (Matzner et al. 2017). In more than 42 hours of camera footage reviewed from the Kvichak River, there were only 20 potential contact interactions, of which three were classified as "Maybe" collisions after close visual examination (Matzner et al. 2017). On only one occasion was an actual contact confirmed, and this was an adult fish that contacted the camera, not the turbine itself.

Development of an Ocean Energy Impact Monitoring System, Scotland (UK) – In 2017, as part of the Development of an Ocean Energy Impact Monitoring System project, the statutory advisor to the Scottish Government on nature conservation, Scottish Natural Heritage, commissioned a review of subsea video monitoring data collected around operational tidal energy projects. Further information about this review, which examined footage from three operational projects, and information about other tidal projects that have used subsea video to monitor nearfield interactions of marine wildlife with turbines is provided in Chapter 3 (Collision Risk for Animals around Turbines).

Marine Renewable Energy Installation (MREI) Development Zone (Wave Hub) and Seabed Cable Installation near Cornwall (UK) – Video monitoring studies were conducted off the north coast of Cornwall (UK) between 2011 and 2015 using baited remote underwater video. The deployed system used a weighted aluminum frame, wide-angle lens, housing, and white light-emitting diode (LED) lights, and an aluminum pole, to which bait was attached, was located near the camera. The system was effective at determining the diversity, abundance, and composition of mobile epi-benthic species in highly dynamic conditions. Other advantages included its cost-effectiveness and flexibility to provide spatial and temporal coverage that can be difficult to obtain using other methods (Bicknell et al. 2019).

European Marine Energy Centre offshore tidal energy test site, Isle of Eday, Orkney Islands (UK) – A combination of optical video and acoustic Doppler current profiler (ADCP) survey techniques was used to examine the presence of Pollack (*Pollachius virens*) temporarily aggregating in shoals around the deployed device from 2009 and 2010. The combined use of video/still photography and ADCP sampling techniques proved useful in the offshore and extreme hydrodynamic environments. Study results indicated that the use of such systems provided preliminary ecological quantitative information, which can help regulatory bodies and developers begin to define ecological interactions with marine tidal energy developments (Broadhurst et al. 2014).

U.S. Navy's Wave Energy Test Site (WETS) in Kaneohe, Hawaii, Fred. Olsen Ltd and Sequim Bay, WA (U.S.) – Stereo-optical cameras with artificial illumination and biofouling mitigation have been a critical component of the Adaptable Monitoring Package (AMP). This optical system, which was developed by the Applied Physics Laboratory at the University of Washington uses two machine vision cameras (Allied Vision Technologies, Manta G-507B) that have 5 mm lenses (Kowa LM5JCM) and high-power LED arrays (Cree CXB-3950 and custom 710 nm red LED arrays) for illumination. Each of these components is packaged in custom waterproof housings and configured on the AMP with camera-camera and camera-light separations of approximately 0.4 m, which minimize optical backscatter (Joslin et al. 2014). Biofouling mitigation measures include a copper ring around the planar view ports of the cameras and lights and mechanical brush wipers (Zebra-Tech Ltd.) (Joslin and Polagye 2015). This system has provided high-resolution imagery of targets of interest throughout deployments of up to six months duration in Sequim Bay, Washington, and at the WETS in Hawaii. From fall 2018 to spring 2019 during a deployment at WETS on board the Fred Olsen Lifesaver wave energy converter, images were used to identify species of reef fish that congregated under the surface buoy. Co-registration of targets identified in both the sonar and optical imagery allows for a higher level of target classification and simplifies data review.

These include the ability to view live VC feeds, contain a dedicated power supply, use more robust recording gear, have easy access to recording equipment, and have remote access via the Internet. Some drawbacks include the added cost for cable, and possible cable damage caused by marine life or ocean conditions. Adding a strength member (normally Kevlar) is often used to increase breaking strength and durability.

Digital video recorders (DVRs) offer many advantages, including greater recording resolution, extended recording ability, long-term storage, video overlays, multi-camera inputs, Internet streaming ability, and greater image reproduction capabilities. The DVR uses software to control external cameras and is very flexible in that cameras can be programmed to record at certain intervals or record only events in which motion is detected (i.e., object detection). In addition, triggered systems (although not a common feature of most COTS systems) can be incorporated such that other instruments (e.g., echosounders) can be used to trigger the camera recording. This can help decrease overall data accumulation for long-term deployments. Accessories to VC recording include video overlays, whether embedded with the recording interface or as an added component. The video overlays can include date/time and recording timers, graphical overlays (altimeter, compass, depth), shapes and other superficial objects for custom themes, and various other features.

Challenges

Data Storage

VCs produce large data files compared to other instrument packages, so they require large amounts of data storage space and create significant challenges when transmitting and analyzing the information. Several strategies can be used to decrease the amount of data for storage, transmission, and analysis. When packaged together with active acoustic instruments, algorithms can be developed to identify objects that may be of interest in the water, such as animals, and a trigger can be sent to the VC signaling the need for it to engage (Underwood et al. 2014). In addition, output from the VC and other instruments can be captured on a ring buffer that is overwritten on a short cycle (usually less than one minute) that is triggered to offload and store data only when the active acoustic trigger indicates (Williamson et al. 2016a). Finally, algorithms can be developed and applied to process video data in order to recognize objects of interest (that might resemble the animals or other items seen in the water) and save only those frames that contain the objects, for later analysis. Assuring that time clocks are accurately synchronized across all instruments and storage devices, as well as enabling consistent metadata across instrument outputs, are essential to assure that the data can be interpreted correctly.

Lighting

Nighttime viewing may be required because observations limited to daylight viewing when ambient light levels are sufficient may not yield representative results of animal interactions (Hammar et al. 2013). If nighttime recording is required, cameras may be augmented with various types of white, red/green, or infrared (IR) filtered lights. The most common type of lights used for underwater viewing are LEDs, whose benefits include a broad light spectrum, long life, and cooler operation. Researchers should verify that the light source will not deter or attract animals, which could interfere with the video observations (most impacts would occur during nocturnal periods). IR lights operating at wavelengths longer than 800 nm can be useful for identifying fish because many species are unaffected by IR, which falls beyond their spectral response range (Lythgoe 1988). The visual pigments of freshwater fish have optimal spectral response within the range of 510 to 545 nm, but most freshwater fish have trichromatic vision, and their visual pigments have absorption peaks around 455 nm (blue), 530 nm (green), and 625 nm (red); coastal marine fish are in the 490 to 510 nm range; whereas deep-sea marine fish are more blue-shifted (470 to 490 nm) (Jobling 1995; Lythgoe 1988). However, IR light has high attenuation in water and is only effective at ranges up to 1.5 m for 700 nm (Kyhn et al. 2012; Matsuoka et al. 1997).

Power Supplies

When setting up a video survey, it is important to know the power consumption of each component, which can be estimated by constructing a power consumption list (online supplementary Table S10.5; online at: *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-environmental-monitoring*). Access to reliable alternating current (AC) power is not always available in the field. For remote situations, 12 or 24 V battery or portable generator power may be the only option, although the U.S. Department of Energy (DOE) Powering the Blue Economy initiative is working to address this challenge by supplying power at sea from MRE devices (LiVecchi et al. 2019). A key factor in battery selection is the consumption rated in ampere-hours for a given component. The ampere-hour rating is the total amount of energy that a battery can deliver for 20 hours at 26°C before the battery drops to 10.5 V before becoming fully discharged. Deep-cycle marine batteries are the preferred type because they are designed to withstand frequent cycles of deep discharge and recharge. Light sources usually require a great deal of power. The light duration can be extended by decreasing the intensity (wattage) of the lights, adding battery ampere-hours (e.g., keeping a larger battery at a higher temperature), changing the battery type (using lithium batteries instead of lead or nickel-cadmium types), or adding a generator or solar-powered battery charger. The power requirements for underwater VCs are usually 12 to 24 VDC (volts direct current) at approximately 110 mA for non-lighted models. In addition, if real-time processing is embedded in the VC the power requirement can be significantly increased (Qi et al. 2018).

Conclusion

Optical cameras, both video and still, have many uses for documenting animal interactions with tidal power generation devices. The best results will be obtained when camera capabilities are well matched to the conditions, the subject of observation, and the data needs. There are many commercial options for hardening systems against ocean conditions and depths, as well as for transmitting or retrieving images and video. Other types of monitoring technology, such as ADCP and acoustic imaging, can be incorporated with optical imaging to provide additional context for fish behavior and interactions. Surface observations made from shore, vessel, or aircraft (including drones) can provide information about and context for what animals may be in the area and some common behaviors in the vicinity of MRE devices, particularly for marine mammals and fish. These observations may help to distinguish and identify particular species and allow for comparisons with underwater video.

10.3. CHALLENGES OF MONITORING AROUND MRE DEVICES

Environmental monitoring of MRE devices is made inherently challenging by the harsh conditions under which the monitoring must take place, the need to manage power for multiple instruments to assure continued monitoring, and the volume of data generated by the suite of instruments deployed. This section provides an overview of the various challenges of environmental monitoring around MRE devices.

10.3.1. SURVIVABILITY/DURABILITY AND ROBUST OPERATION

Conditions at locations suitable for the development of marine energy are inherently challenging for engineering durable and robust systems. Namely, forces from high-energy waves and currents compound the customary challenges of working in marine environments including pressure, corrosion, and biofouling. In addition, deployment, maintenance, and recovery operations may be limited because of infrequent calm weather windows, short periods at slack tide, short daylight windows in high latitudes, and safety concerns for personnel associated with swift current and large waves.

Hydrodynamic Forcing

Fluid-structure interactions in flowing water lead to hydrodynamic forces of lift (perpendicular to the direction of flow) and drag (parallel to the direction of flow) acting on submerged bodies. Currents tend to be stronger closer to the surface and weakest at the seabed. Monitoring systems operating in high-flow environments must be secured to prevent sliding, flipping, floating away, or structural failure caused by drag and lift. Three main methods are employed, typically in tandem, to limit these outcomes: reducing the drag and lift coefficients by streamlining exposed components, reducing exposed frontal area, and increasing the weight of the monitoring system. The former two decrease the magnitude of forcing, while the latter one assists in resisting its effects (i.e., by providing friction and leverage). Conversely, monitoring systems may be affixed to more permanent or secure features like pilings, but will likely involve increased cost and complexity. In addition to lift and drag, vibrations or strumming induced by vortex shedding can lead to hardware loosening and increased structural fatigue, and can affect the quality of data derived from acoustic sensors. In all cases, proper engineering analysis and design are critical for system survivability.

Forces from waves manifest through several pathways. Below the surface, waves induce the circular flow or orbital motion of water, decreasing in magnitude with depth, and resulting in lift and drag forces on structures, as described above. The hydrostatic force of a wave is proportional to its height. Designers of monitoring systems built to withstand wave forcing may take several approaches: deploying the system deep enough to avoid orbital motion, designing structures to follow waves instead of absorbing energy from them, avoiding the surf zone, and/or using durable materials and structural designs.

Corrosion and Biofouling

Two environmental effects limit the durability and survivability of submerged structures and instrumentation: corrosion and fouling. Corrosion is the degradation or removal of material as a result of chemical interactions between the environment and structures, and it is typically prevalent on metals. Corrosion occurs naturally in the environment and accelerates in response to the creation of galvanic circuits between coupled dissimilar metals in the presence of an electrolyte, where more "anodic" materials are consumed (The Electrochemical Society 2011). Corrosion rates vary based on many factors and may be hard to predict. Seawater is a particularly corrosive environment because of its high conductivity. Galvanic circuits in seawater yield corrosion rates 5 to 12 times greater than if no electrolytes were present, while rates may increase two to five times in freshwater (The Electrochemical Society 2011). Solutions to corrosion issues include using less reactive or "cathodic" materials such as titanium or certain stainless-steel alloys at increased cost, coatings and anodization, or isolating dissimilar metals using nonconducting materials. Strongly anodic materials should not be used in the presence of strongly cathodic ones. Alternatively, sacrificial anodes made of zinc or other highly reactive metals can be employed to protect more cathodic materials from natural or galvanic corrosion (The Electrochemical Society 2011). Ultimately, experience shows that under certain circumstances, even parts made of titanium can corrode, particularly when exposed to low-oxygen, high-temperature conditions (Pang and Blackwood 2016).

Biological growth on submerged structures, commonly referred to as "biofouling" (see Chapter 6, Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices), may degrade instrument performance or interfere with critical components such as recovery equipment. The fouling process begins with the formation of thin biofilms (microorganisms) on exposed surfaces, followed by the colonization or recruitment of larger macro-organisms (Bixler and Bhushan 2012). Flora and fauna vary by region and depth and may be inconsistent from season to season or year to year. Biofouling can interfere with transducer elements, cover optical ports, clog bearings, and increase drag. Considerable effort over many decades has gone into preventing or mitigating biofouling, yielding solutions including engineering for specialized surface properties, chemical-based coatings or paints, ultraviolet and gamma radiation, ultrasonic vibration, electrical current, and even explosives (Bixler and Bhushan 2012). Mechanical wipers integrated on the AMP have been effective at preventing growth on critical components (Figure 10.9). Regardless of the mitigation method selected, system designers must also be careful not to adversely affect or interfere with the environment they are attempting to study.

Pressure and Sealing

Commercially available instruments and instrumentation subsystems intended for submersion are rated to specific depths and sealed to prevent structural collapse caused by pressure and water ingress. Similarly, individual enclosures may be rated by the level of environmental protection. For example, ingress protection codes and standards, published by the IEC specify ratings indicating protection from splashing, water jets, or submersion (IEC 2013). Sealed enclosures containing instrumentation or electronics introduce additional challenges, including temperature management, connectivity, and maintenance. Common practices to mitigate these including filling housings with mineral oil or other inert incompressible fluids, using wet-mate connectors, and using magnetic or reed switches. Experience to date with MRE monitoring instruments has shown connectors to be the most common point of failure. Many connectors used for offshore oil and gas development are designed to effectively seal at greater depths than is typical for MRE deployments.

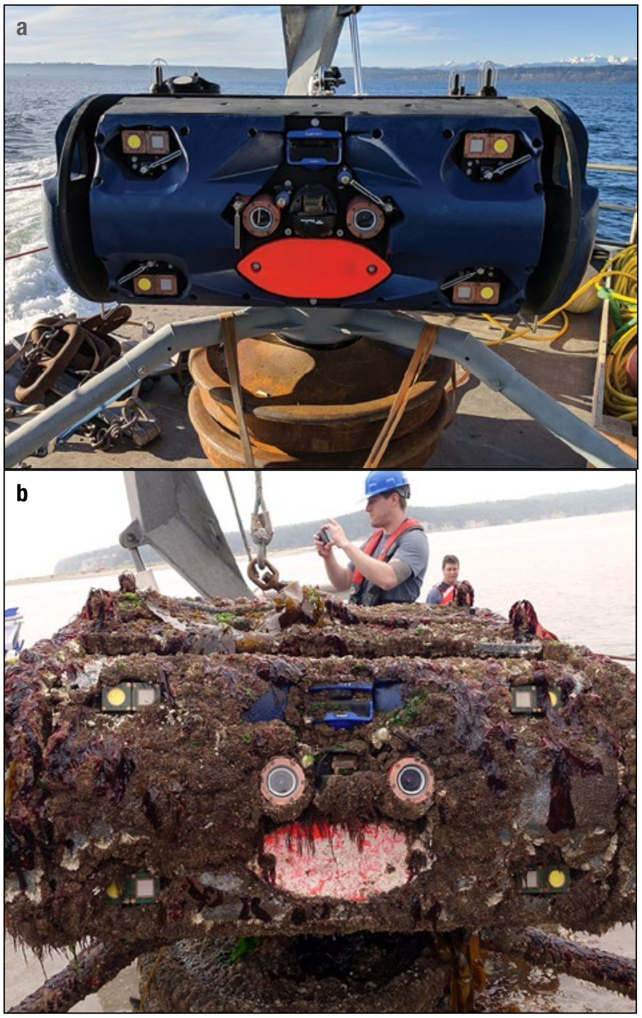

Figure 10.9. The Adaptable Monitoring Package (AMP), before (a.) and after (b.) deployment for 18 weeks in Sequim Bay, Washington, United States. (Photos courtesy of Applied Physics Laboratory, University of Washington)

Deployment, Maintenance, and Recovery

Deployment, maintenance, and recovery of monitoring systems where marine energy resources are strong is a major challenge. Indeed, at sites where the resource is the strongest or most consistent, the access to and ultimately the availability of the systems may be most limited (O'Connor et al. 2013). Scheduling of marine operations depends on vessel and crew availability, which often requires weeks or months of advanced planning. The types of vessels required to operate in high waves or strong currents are often rare and more expensive. For tidal energy sites, the high degree of predictability of the resource aids in planning operations. However, performing tasks during short slack water windows increases risk to personnel and equipment if complications arise. Low wave weather windows are harder to predict, but favorable conditions may last for many hours or days.

10.3.2. DATA MORTGAGES

Reliable detection of rare events, such as interactions between a marine mammal and a tidal turbine, requires monitoring over long periods (on the order of days to years) to satisfy licensing conditions. However, continuous acquisition of data from medium- and high-bandwidth instruments, such as optical cameras or multibeam sonars, results in unmanageable volumes of data (colloquially referred to as a "data mortgage"). For example, a single 5-megapixel camera with a 10 Hz frame rate could accrue more than 2 TB of uncompressed images in a single day. This challenge is compounded when multiple instruments are used in an integrated instrumentation package. While image compression can significantly reduce the data volume, post-processing or human review of the collected data still present a significant challenge. As a result, data mortgages can result in monitoring that is "data-rich, information-poor" (Wilding et al. 2017).

10.3.3. POWER AVAILABILITY AND MANAGEMENT

Providing power to instrumentation is a key challenge to achieving sustained, high-fidelity environmental monitoring at MRE sites. Instruments may be deployed in deep water, far from shore, or in hard to access locations. Power delivery can be accomplished through one or a combination of the following methods: running a power cable to the deployment location, including individual instrument batteries or a centralized battery bank, and coupling to an in situ power generation source.

Cabled Systems

Cabled operation offers the highest level of power and typically enables the ability to stream or easily access data from shore. Cabled observatories currently provide an unprecedented ability to observe the oceans (Smith et al. 2018). The characteristics of the cable are determined by the requirements of the instruments. Depending on these requirements, the cable may conduct AC or DC electricity. Most of the instruments and systems described in this chapter accept external power over a range of 5 to 48 VDC. A higher export voltage than listed for the instruments must be run to account for voltage drop across the cable itself and during startup (inrush current) or high sampling events. Therefore, one or several DC/DC converters are required to step the voltage down to instrument level. If AC power is used, a rectifier or AC/DC converter will be necessary. Additional converters add to system complexity and generate heat. The cable itself and operations to run and secure it represent major project expenses. The cable is a single point of failure for the systems that rely solely on it for power. Ultimately, the major trade-off for employing a cable is access to high-power, high-fidelity, and constant communications at high cost.

Battery-powered Systems

Many of the instruments mentioned in this chapter are designed to be pre-configured and run autonomously using their own internal batteries. Consequently, they have been designed to use small amounts of power and/or have adjustable sampling rates and duty cycles. For many of them, much of their volume is occupied by batteries (e.g., ADCPs). Systems running on batteries can be designed to be deployed anywhere. The major trade-off for relying on internal batteries is broad applicability and reliability countered by limited duration, a lack of operational feedback, and no native synchronization of measurements. Integrated monitoring systems can also employ larger, centralized battery banks to power instruments. This method may extend the duration and enable centralized control of duty cycles. However, similar to cabled systems, DC/DC power converters are necessary, and they add complexity and heat generation to such systems. Other challenges of using batteries are their increased volume and weight, the safety and transportability for certain chemistries (e.g., lithium-ion), and the high cost to seal large volumes.

Marine Energy-powered Systems

Ocean observation systems were identified as a key near-term market for the marine energy industry in the U.S. DOE Powering the Blue Economy report (LiVecchi et al. 2019). This option has the potential to provide power between a cable and a battery bank anywhere there is sufficient resource availability. This concept has been demonstrated for a WEC at the WETS in Kaneohe Bay, Hawaii, U.S. The WEC, when coupled to a battery bank and backup solar panel allowed the AMP to reach 84 percent uptime over a 108-day deployment period (Joslin et al. 2019). Other monitoring systems use marine energy for motion or to perform profiling, thereby offsetting electrical demands (Manley and Willcox 2010; Pinkel et al. 2011). Despite promising potential, challenges remain for this method. First, the maturity and technical readiness of most marine energy systems is still low, and their reliability has not been sufficiently demonstrated. Second, the presence of the converter may interfere with the functioning of instruments or diminish the quality of measurements (e.g., sound from a WEC may dominate hydrophone recordings). Third, other, more mature renewable technologies like solar or wind power may perform similarly or better if a surface presence is possible. Finally, the costs of marine energy systems are high or largely unknown, likely rivaling those of cable installations (depending on the distance from shore). National laboratories, academic universities, and industry are conducting further research and commercial ventures to meet these challenges.

10.4. INTEGRATED MONITORING PLATFORMS CURRENTLY USED TO MONITOR MRE DEVICES

A variety of integrated monitoring platforms have been developed and deployed for monitoring MRE devices. They include a series of autonomous and cabled platforms that have an array of monitoring instruments integrated for power requirements and duty cycles. This section provides an overview of the various integrated monitoring platforms that have been developed and deployed.

10.4.1. ADAPTABLE MONITORING PACKAGE

The AMP (Figure 10.10) is an instrumentation platform developed to provide continuous underwater monitoring for multi-month deployments around marine energy devices using autonomous data processing and real-time target detection and tracking (Cotter et al. 2017, Polagye et al. 2020). Deployments to date have included both cabled and autonomous systems, on both bottom landers and surface buoys. More than two years of sea testing have demonstrated the systems' monitoring capabilities in wave climates, high current channels, and onboard vessels.

The backbone of the AMP hardware is a power and communications system that allows any cabled instrument to be integrated into the platform. To date, these instruments have included stereo-optical cameras with lights and wipers, acoustical cameras, multibeam sonars, echosounders, hydrophones, ADCPs, fish tag receivers, actuators, and water-clarity instruments. The combina-

Figure 10.10. The Adaptable Monitoring Package (AMP). An integrated subsea instrument package developed by the University of Washington that is used to monitor marine renewable energy devices. (Image courtesy of Applied Physics Laboratory, University of Washington)

tions of these instruments can enable a wide range of monitoring and tracking capabilities depending on the objectives. The data acquisition, processing, and management for this system use custom software that integrates the operation and control of each instrument. Real-time algorithms have been implemented to perform target detection, tracking, and classification of data from the imaging sonars and hydrophones, which are used to trigger artificial illumination for the optical cameras and data acquisition from all sensors. This real-time continuous data processing allows the system to capture rare events without accruing a large data mortgage and minimizes bias on marine life related to artificial illumination.

To date, instrument settings and target-detection thresholds have been tuned during the first phase of the deployment to fit the site and monitoring goals. The primary targets of interest that have been detected have been marine mammals (e.g., seals) and diving seabirds in the Puget Sound, Washington, U.S., and large individual fish, squid, and schools of small fish elsewhere. These target-detection and -tracking capabilities have been assessed with the help of cooperative targets in the form of divers, surface vessels and drifters towing targets, and underwater vehicles.

10.4.2. FUNDY ADVANCED SENSOR TECHNOLOGY–ENVIRONMENTAL MONITORING SYSTEM

FORCE in Nova Scotia, Canada, has been pursuing an integrated environmental monitoring platform as part of the Fundy Advanced Sensor Technology (FAST) program for environmental monitoring of tidal turbines in Minas Passage, in the Bay of Fundy. This cabled subsea Environmental Monitoring System (i.e., FAST-EMS) includes (1) a Tritech Gemini 720is multibeam imaging sonar mounted on a Kongsberg pan and tilt device, (2) a NORTEK AWAC ADCP, (3) two Ocean Sonics Ltd. icListen high-frequency hydrophones, and (4) a sculpin subsea camera. The FAST-EMS platform (Figure 10.11) is intended to be deployed near gravity-based tidal turbines deployed at FORCE, but its deployment location is limited by the useful range of the Gemini 720is multibeam sonar (<120 m) and the operational capabilities of the marine assets at the target deployment site. The platform is cabled to shore to provide power and data transferability, and the associated equipment enabling the functioning of the monitoring instruments includes a termination canister and a multiplexer linking to the subsea power cable. Onshore assets at FORCE include a suite of supporting infrastructure for data transferability that has been demonstrated to provide faster upload of multibeam data than the rate at which those data could be collected (i.e., 100 Mbps up/down capabilities).

Multiple short-term trial deployments of the cabled FAST-EMS platform conducted near the FORCE tidal demonstration site to assess system performance revealed that monitoring instruments performed well under relatively benign marine conditions. However, more work with electrical connectors and data transfer with lengthier subsea cables is required to advance FAST-EMS beyond the research and development stage to an integrated monitoring platform that can be used reliably for monitoring interactions of marine animals with tidal turbines at the FORCE tidal demonstration site.

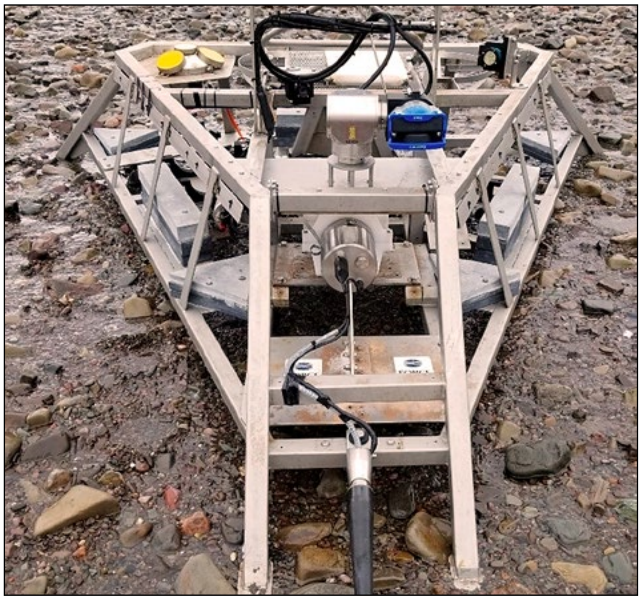

Figure 10.11. Fundy Ocean Research Centre for Energy (FORCE)'s Fundy Advanced Sensor Technology Environmental Monitoring System (FAST-EMS) integrated and cabled monitoring platform positioned on the FORCE beach. (Photo courtesy of FORCE)

10.4.3. FLOW, WATER COLUMN AND BENTHIC ECOLOGY 4D

The FLOWBEC-4D project investigated the environmental and ecological effects of installing and operating MRE devices. The FLOWBEC seabed platform (Figure 10.12) was developed, which integrated multiple instruments to concurrently monitor the physical and ecological environment in marine energy sites (Williamson et al. 2016a). Onboard batteries and data storage provided continuous recording of a 14-day spring/neap tidal cycle to investigate the predictable behavior of animals over tidal and diel cycles (Williamson et al. 2019). The self-contained platform allows measurements to be taken adjacent to marine energy structures and in areas free of such devices to investigate ecological (Fraser et al. 2018) and hydrodynamic changes (Fraser et al. 2017b) around MRE structures. Developments are under way to extend the battery-powered deployments using instrument triggering (i.e., only using higher power instruments during detected periods of interest). A cabled interface providing real-time data and a continuous power supply have also been developed to extend monitoring endurance.

Multiple instruments measure the behavior and interactions of fish, diving seabirds, and marine mammals. An Imagenex 837B Delta T multibeam echosounder (vertical swath aligned with the tidal flow) was synchronized with an upward-facing Simrad EK60 multifrequency (38, 120, 200 kHz) scientific echosounder sampling once per second. A SonTek/YSI ADVOcean 5 MHz Acoustic Doppler Velocimeter was used to measure mean flow and turbulence. A Nortek Signature 500 kHz ADCP was used to take hydrodynamic measurements of flow and turbulence throughout the water column. A camera has recently been integrated to confirm species identification when lighting and visibility permit, and a hydrophone has been integrated to monitor ambient noise and detect vocalizing cetaceans.

Crucially, these instruments operate simultaneously without interference using a modular and adaptable control system to allow the concurrent measurement of animal behavior and explanatory variables (Williamson et al. 2017), and to investigate comparisons and transferability between sites (Wiesebron et al. 2016). Co-registration between instruments also allows measurements to be validated, and ground-truthing of bird and mammal observations was provided by concurrent shore-based observations or separate ground-truthing surveys.

A total of six battery-powered deployments have been completed at a variety of wave and tidal stream energy sites in Scotland—both EMEC (Orkney, Scotland) and MeyGen (Pentland Firth, Scotland)—including around the Atlantis and OpenHydro tidal turbine support structures and in reference areas, free of devices.

10.4.4. SEA MAMMAL RESEARCH UNIT MONITORING SYSTEM

The Sea Mammal Research Unit (SMRU) at the University of St Andrews in Scotland developed and deployed a 12-hydrophone PAM system on the foundation of an operational tidal turbine at the MeyGen demonstration array in Scotland (Figure 10.13). The hydrophones and acquisition electronics were mounted on the structure prior to its deployment and were connected into the turbine systems for power and data export.

The primary target species was harbor porpoise, which echolocate at 130 kHz, so hydrophones were sampled at 500 kHz, generating ~1 Tb of raw data per day. Data

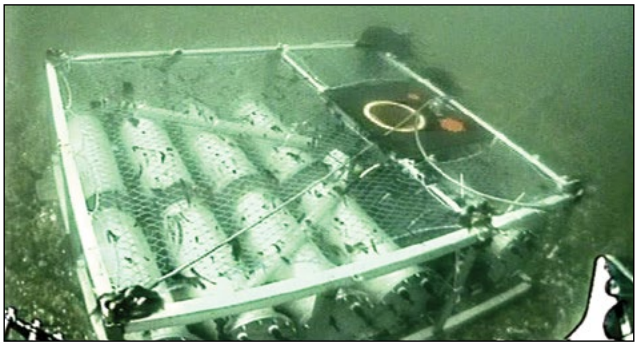

Figure 10.12. The FLOWBEC-4D platform during deployment at the European Marine Energy Center in the United Kingdom. (From Williamson et al. 2016a)

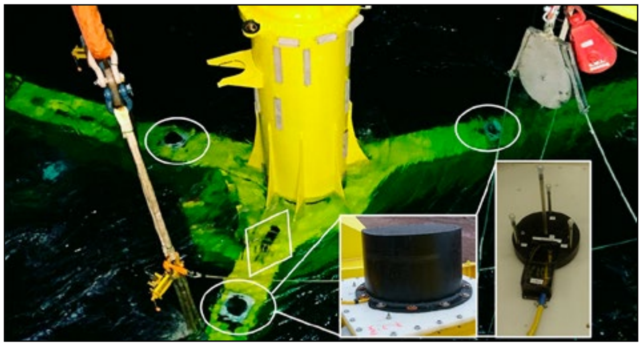

Figure 10.13. Photograph of the MeyGen turbine support structure during installation showing the locations of the three hydrophone clusters. Insets are photographs of a tetrahedral hydrophone cluster and its protective cowling. (Photo courtesy of SIMEC Atlantis Energy)

were sent to the shore via optical fiber in the turbine export cable and processed in real time using PAMGuard software (Gillespie et al. 2008b). The system was operational between October 2017 and October 2019. Data were manually screened offline to confirm species and to localize clicks in three dimensions. Several hundred porpoise tracks around the turbine have been acquired and are being analyzed for evidence of fine-scale avoidance behavior.

The turbine connection system is currently being reconfigured for a new platform, the marine mammal HiCUP (High Current Underwater Platform) (Figure 10.14) to be deployed in late 2020. The new system is built into a gravity-mounted platform that also includes two Tritech Gemini 720i multibeam imaging sonars, which enable the system to also detect and track grey seals (*Halichoerus grypus*) and harbor seals, which rarely vocalize under water.

Two sonars are used to cover the full (~20 m) height of the turbine blades, and also to extract a vertical position for animals based on the relative intensity of the target on the two sonars (Hastie et al. 2019a). Automatic detection and tracking reduces the need for operator screening of large amounts of sonar data (Hastie et al. 2019b). The Tritech system was selected because it is effective at detecting marine mammals at ranges up to ~50 m and does not elicit overt behavioral responses in seals (Hastie et al. 2019a). A single tetrahedral cluster of hydrophones is mounted close to the sonars to give horizontal and elevation angles to sounds, and provides species identification, separating clicks from porpoise and dolphin species, as well as helping to classify seals. Both PAMGuard and software developed for the PAM data acquisition control system are open source and freely available.

10.4.5. INTEGRATED MONITORING POD

Under the Energy Technologies Institute (ETI)'s Reliable Data Acquisition Platform for Tidal (ReDAPT) project, EMEC tested its novel Integrated Monitoring Pod (IMP) at its tidal test site at the Fall of Warness, the Orkney Islands. The first of its kind pre-commercial prototype (Figure 10.15) has been designed to operate in high-velocity tidal flows. It integrates a variety of instruments to undertake comprehensive concurrent environmental measurements, supply real-time data, and provide improved characterization of high-energy marine environments. Instruments onboard the IMP

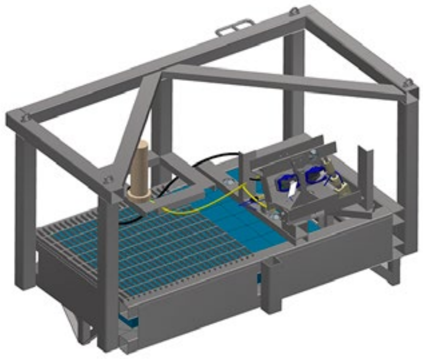

Figure 10.14. Schematic of the marine mammal High Current Underwater Platform (HiCUP) developed by the Sea Mammal Research Unit (SMRU) at the University of St Andrews. (Image courtesy of SMRU, University of St Andrews)

include hydrophones, active sonar system (provided by Ultra Electronics), underwater CCTV, ADCP, and other standard equipment to measure temperature, salinity, and density. It can be connected to the shore via a subsea cable to facilitate 24/7 real-time data collection to deliver live data feedbacks to EMEC for use by clients accessing the test site. Making the real-time data feeds available to clients assists in device design, enabling more accurate assessment of device performance and support during operations and maintenance planning. The ReDAPT project was commissioned to boost public, industry, and regulatory confidence in the tidal energy sector.

The IMP is set up as a plug-and-play prototype in which it is possible to install additional instruments as required. More recently in 2017, through the In Situ Turbulence Replication Evaluation and Measurement project, the pod was reinstalled with a Rockland Scientific turbulence instrument onboard. The instrument

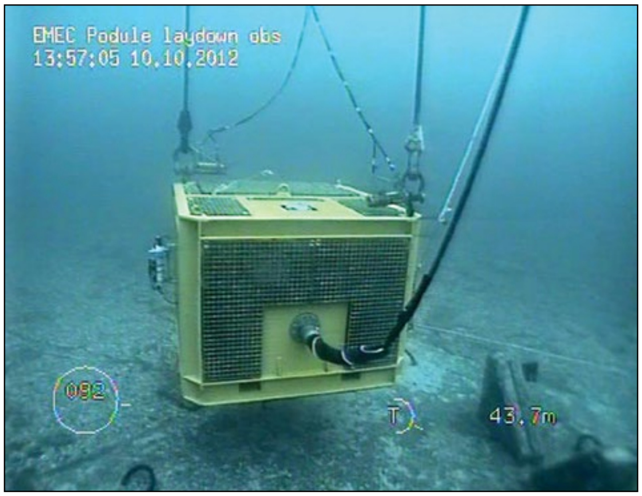

Figure 10.15. The European Marine Energy Centre (EMEC)'s Integrated Monitoring Pod (IMP) during deployment under the Energy Technologies Institute (ETI)'s Reliable Data Acquisition Platform for Tidal (ReDAPT) project. (Photo courtesy of EMEC)

combines standard flow measurement technology (acoustic electromagnetic) with novel non-acoustic measurement technology (shear probes). Plymouth Marine Laboratory has used the pod to test marine coatings designed to prevent biofouling, corrosion, and abrasion, and Heriot-Watt University has installed test panels to characterize biofouling assemblages typical of the high tidally influenced sites. The IMP builds on a comprehensive monitoring system developed by EMEC, which uses marine radar, a meteorological station, VCs, drifting acoustic surveys, ROV surveys, and onshore wildlife observations.

10.5. LESSONS LEARNED FROM MONITORING ACTIVITIES

Building on the information about collision risk to marine animals from Chapter 3 (Collision Risk for Animals around Turbines), our collective understanding of the effects of MRE devices on marine animals has improved because of advances made in methodological processes, innovations in monitoring technologies, the integration of state-of-the-art instrumentation on autonomous and cabled subsea monitoring platforms, and their subsequent deployments in harsh marine conditions. These improvements stem from the series of largely undocumented failures and setbacks experienced by those who pioneered monitoring activities for the nascent MRE industry and initially employed standard oceanographic and remote-sensing technologies in this new context. Although the knowledge gained from this process has greatly advanced monitoring capabilities, ongoing challenges remain, including the need to assure the durability of sensitive equipment; power availability and management for integrated monitoring systems; and continuous data collection, storage, and analysis.

Integrated monitoring platforms, as well as other configurations of remotely mounted instruments can help document the most challenging interactions between marine animals and MRE devices, and especially move collision risk assessments beyond a modeling exercise to the collection of empirical data for quantifying the risk. However, there are currently no commercially available "fit for purpose" instrumentation packages, and monitoring still relies on oceanographic, hydroacoustic, and other instruments that are intended for use in more benign marine conditions. These technologies must be integrated, configured, tested, and validated in new ways to suit dynamic marine environments and to detect critical interactions between marine animals and MRE devices. The electronic integration of instruments on a platform is as important as their physical integration, and despite establishing duty cycles, it is important to recognize that interference between instruments is likely, unless engineering measures are adopted to prevent it, and cannot be ignored. The volume of data collected through monitoring activities and the cost of analyzing the data remain important obstacles. The processes for onboard collection of monitoring data need to be weighed against the collection of excessive amounts of data and the concerns about missing rare events and the future potential use of those data.

10.6. RECOMMENDATIONS FOR QUALITY DATA COLLECTION, MANAGEMENT, AND ANALYSIS

International- and national-level agreements on the suite of instruments required for monitoring MRE devices and for documenting interactions that cannot be resolved by research studies alone are needed. Research studies should be aligned with critical questions posed by licensing requirements and dictated by the results of ongoing monitoring and research campaigns. Modeling studies remain an essential part of understanding the environmental risks of MRE devices and should be employed, as appropriate. For cases where no data currently exist (e.g., changes in oceanographic systems), models can be employed to help guide monitoring programs for when MRE arrays are established. Where few data currently exist (e.g., collision risk), models can be used to iteratively improve monitoring studies. For instances where data are readily available and can be compared to regulatory thresholds or other measures, we should continue to iterate and develop models that will decrease the need for measurements at every site at which an MRE device is deployed.

The data mortgage challenge can be addressed through the collection of data on a sparse duty cycle (e.g., only record five minutes of data every hour). However, this approach would likely miss rare events of interest. Alternatively, automated data processing can be implemented to identify periods of interest in the collected data. When implemented during post-processing, automated data processing can be used to limit human review to periods of interest, reducing the significant effort required to extract insight from large datasets. When implemented in real time, automated data processing can be used to limit data acquisition to periods of interest and reduce the volume of data that requires archival storage. This approach has been used for the AMP (Cotter et al. 2017) and for PAM (Malinka et al. 2018).

Recently, there has been a push to improve automatic data processing methods for environmental data derived from MRE sites to decrease the volume of data that must be analyzed, the rate at which the data can be analyzed, and increase the accuracy of results. Here, we provide a brief overview of recent advancements in the automated processing of passive acoustics, active acoustics, and optical camera data at marine energy sites.

10.6.1. PASSIVE ACOUSTICS

Automated detection and localization of vocalizing marine mammals can be used to quantify the presence and behavior of vocalizing marine mammals. PAMGuard (www.PAMGuard.org; Gillespie et al. 2008b), an open-source software package for automated processing of passive acoustic data, has been widely used for the processing of data from marine energy sites. For example, Malinka et al. (2018) used PAMGuard to detect marine mammal clicks and tonal sounds in real time, and this information was used to limit data acquisition to periods when a vocalization was detected. These detected vocalizations were later manually reviewed for accuracy. Even though mechanical sounds from the monitored tidal turbine caused occasional false detections, the data review effort was significantly reduced compared to review of continuously acquired data. Other examples of automated detection of marine mammal vocalizations using PAMGuard can be found in publications by Fernandez-Betelu et al. (2019), Macaulay et al. (2017), and Wilson et al. (2013).

10.6.2. ACTIVE ACOUSTICS

The most common approach to automatic processing of multibeam sonar data is to detect moving targets in the image and track those targets through the sonar swath (Cotter et al. 2017; Jepp 2017; Lieber et al. 2017; Williamson et al. 2017). In turbulent environments, it may be necessary to first isolate portions of the water column that are dominated by noise (Fraser et al. 2017a). Target-tracking data can be used to narrow down and guide the review that is carried out by humans, allowing them to compare the size, shape, and speed of targets. Cotter et al. (2017) implemented multibeam sonar target tracking in real time and used it to limit data acquisition to periods when targets were predicted to be present. This approach recorded an estimated 99 percent of targets with a 58 percent true positive rate. Cotter and Polagye (2020) evaluated real-time classification of these target tracks and found that a random forest algorithm distinguished between the biological and non-biological targets with a 97 percent true positive rate.

The processing of echosounder data typically involves the separation of pixels that are above a static minimum backscatter strength threshold (Simmonds and MacLennan 2007). However, at marine energy sites, this approach is generally not viable because of variable background backscatter strength levels and the presence of entrained air that has backscatter strength comparable to targets of interest (Fraser et al. 2017a). As a result, the processing of echosounder data at marine energy sites has relied heavily on human review and frequently excludes the top of the water column (Viehman et al. 2018; Wiesebron et al. 2016). To combat this, Fraser et al. (2017a) developed an adaptive filtering approach to suppress background noise in echosounder data using a moving median filter and morphological filtering to separate targets of interest from entrained air. This approach was found to reliably detect fish schools throughout the entire water column in echosounder data collected from a bottom platform at the Fall of Warness in Scotland.

10.6.3. OPTICAL CAMERAS

Automated data processing for optical camera data at marine energy sites is complicated by characteristically low water clarity, high water velocity, and variable ambient light. Most existing algorithms developed for target detection and classification in underwater camera imagery have focused on brightly colored coral fish or deep-water environments with constant artificial illumination, and are not suitable for data collected at marine energy sites (Xu and Matzner 2018). Xu and Matzner (2018) applied a deep neural network, YOLO v3 (Redmon and Farhadi 2018), to automate the detection of fish in optical camera data from two tidal energy sites and one conventional hydropower site. The YOLO algorithm was implemented in EyeSea (Matzner et al. 2019), an open-source application framework for manual or automated annotation of optical camera imagery that can be extended to include new processing algorithms. When the model was trained using optical camera data from the Voith Hydro turbine deployment at EMEC, it was able to identify fish with 75 percent precision and 50 percent recall in validation data from the same test site. However, when trained using data from other sites, the model was found to not generalize well to data collected by different cameras at different locations. Ongoing research at the Applied Physics Laboratory–University of Washington aims to expand upon the work by Xu and Matzner (2018) to develop a generalized stereo camera fish segmentation algorithm for environmental monitoring at marine energy sites. This work uses a stereo camera extrinsic relationship to both increase algorithm robustness and optionally ignore small fish that tend to gather near cameras on marine energy converter environmental monitoring instruments (Mitchell Scott, personal communication).

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NOTES

Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines

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REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
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