FORWARD 2030

Integrated Environmental Monitoring System: Design Specification

Deliverable D9.5

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Contents

List of Figures

List of Tables

Executive summary

Uncertainties surrounding the environmental impact of large-scale floating tidal energy arrays remains a significant regulatory challenge and thus barrier to their commercialisation. The potential for protected marine species to encounter and collide with operational turbines remains one of the highest-priority concerns which is managed through a precautionary regulatory approach. Post-installation monitoring is often required as a licensing condition, with the aim of improving knowledge of near-field interactions between wildlife and operational devices and validating collision risk model predictions submitted during the consenting process. However, collision risk is an active area of research which widely recognises the technical challenges in deploying monitoring instrumentation in high-flow environments. This results in a lack of *in situ* species data available to improve existing collision risk models, which are extremely sensitive to assumptions about species behaviour parameters such as avoidance or fine-scale evasive responses.

Under the FORWARD2030 project an Integrated Environmental Monitoring System (IEMS) will be delivered as one of the project's three market uptake innovations, which aim to assist with consenting of the 2030 MW pipeline and overall enhance environmental and societal acceptance of large-scale floating tidal arrays. The IEMS will incorporate technologies to monitor fine-scale species interactions around the Orbital Marine Power O2 turbine, in order to capture meaningful data that can be used to improve collision risk estimates and inform how future iterations of the IEMS could integrate with the core design of the forthcoming O2.X.

Integrated monitoring platforms with different sensor configurations have been developed to date by various research institutions for the purpose of marine species detection in challenging, high-flow environments. However, while a number of successes and lessons learnt have been reported from these studies, existing platforms have either been designed for seabed deployment or attachment to a fixed turbine, with a scarcity of available experience in developing integrated monitoring for surface-floating turbines.

The purpose of this document is therefore to provide requirements drawn from lessons learnt communicated in the literature to inform the collaborative design, build and deployment of the IEMS. The proposed IEMS design concept is a structurally simple pole-mounted combination of acoustic and optical instrumentation which is accessible to personnel to minimise operational complexity. It is recommended that the IEMS undergoes iterative development to allow field testing of each hardware component and data processing protocols. This will subsequently feed lessons learnt into interface adjustments in future iterations of the IEMS to progress overall reliability of the system for long-term fine-scale behavioural monitoring around floating tidal turbines.

1 Introduction

1.1 FORWARD2030

Ensuring the European energy transition meets net zero targets by 2050 requires securing significant investment and public support of low-carbon renewable energy generation. Tidal stream energy is an emerging sector that utilises the predictability of tides to deliver a non-intermittent power supply with a low carbon footprint due to the energy density of water and close proximity to coastlines. Ocean Energy Europe (OEE) reports for 2021 a growth of tidal energy installations with 30.2 MW deployed throughout Europe since 2010, of which 11.5 MW was operational in the water through 2021 (OEE, 2022). Following a post-pandemic increase in tidal stream capacity from 2020 to 2021, OEE now anticipates the next major capacity increase in tidal stream around 2025 with a new generation of tidal arrays in the pipeline (OEE, 2022). Ocean Energy Europe's 2030 Ocean Energy Vision presents high and low-growth scenarios for the tidal stream sector to 2030, with a high-growth projection of 2,388 MW installed capacity by 2030 with cost reductions to around €90 MWh^{-1} (OEE, 2020).

In line with the vision's high-growth scenario, the EU Horizon 2020 FORWARD2030 ("Fast-tracking Offshore Renewable energy With Advanced Research to Deploy 2030 MW of tidal energy before 2030") project has been established to deliver a series of high-impact cost reductions to achieve a breakthrough 2030 MW of tidal stream deployment by 2030. Led by Scottish-based tidal energy technology developer Orbital Marine Power, the project partnership consists of SKF GMBH and SKF SVERIGE AB (major global manufacturer with over 100 years' experience in rotating machinery), LABORELEC (research institution of ENGIE, the third largest electrical utility in the world), University of Edinburgh and University College Cork (globally renowned experts in techno and socioeconomic analysis and marine spatial planning), and the European Marine Energy Centre (world leading marine energy demonstration centre and internationally accredited test laboratory). Orbital Marine Power has pioneered innovative floating tidal technology since the company's inception in 2002. Refinement and optimisation of the company's previous SR2000 device, then cited as the world's most powerful tidal turbine, has led to the current 74 m 2 MW O2 design. FORWARD2030 will support continued innovation on Orbital's forthcoming O2.X technology design, to further reduce LCOE of the technology by 25%.

Recent practical resource estimates indicate that tidal stream energy could contribute 11% (34 TWh y^{-1}) to the UK energy mix by 2050 (Coles et al., 2021). "Practical resource" defines the annual yield potential using tidal stream technology, after economic, environmental, regulatory and social constraints have been applied. As the tidal sector progresses from single device and small-scale array demonstrations to larger scale arrays in support of decarbonisation targets, it is crucial to understand and solve these constraints to maximise practical tidal stream energy resource.

One of the biggest challenges to the commercial viability of large scale tidal energy arrays is uncertainty surrounding the environmental impact of large scale arrays, which creates a barrier to consenting and has the potential to increase public opposition to development. FORWARD2030 will incorporate a programme of environmental monitoring as one of three market uptake innovations, with the aim to assist with consenting of the 2030 MW pipeline and overall enhance environmental and societal acceptance with regard to scaling up to tidal arrays. Under Work Package 9 (WP9 Operation and monitoring) of the project, the European Marine Energy Centre (EMEC) will lead the delivery of a monitoring hardware system and deployment campaign focused on key biodiversity and environmental risks, presenting a verified mitigation and monitoring tool for regulators and developers. It aims to advance understanding on ecosystem dynamics while addressing fundamental decision-making concerns and critical knowledge gaps of large-scale deployments.

WP9 Environmental scope and deliverables

The scope of environmental work in FORWARD2030 was developed to inform high-priority regulatory concerns and emerging research themes surrounding potential environmental impacts of large-scale arrays. The risk of collision with rotating blades of tidal devices by marine mammals, fish and diving seabirds is of principal concern in the consenting process and is closely scrutinised where there is a potential risk to protected or vulnerable species. While significant research progress has been made to build an evidence base on near and far-field wildlife responses to the physical presence of operational tidal devices, technical issues and challenges remain in collecting distribution and behavioural data of mobile species at fine scales (metres) around a device (ORJIP Ocean Energy, 2020). Such data is crucial to validate and improve predictive collision risk models which are submitted to regulators to support the impact assessment process in consenting (see Section 2 for further detail).

To address this challenge EMEC will design, engineer, and performance test an IEMS for floating tidal energy arrays, as a key focus of the FORWARD2030 environmental monitoring activities and the subject of this document. The IEMS will be tested with Orbital Marine Power's O2 device to inform how future iterations of the IEMS can integrate with the core design of the O2.X.

Further monitoring will be performed to understand site-wide usage and potential displacement by marine mammals, fish and diving seabirds across EMEC's Fall of Warness tidal test site, where the O2 device is currently berthed:

- An existing predator-prey interaction model will be integrated with device operational information and onboard acoustic doppler current profiler (ADCP) data, to demonstrate the influence of local hydrodynamic forcing due to the presence of the device and its effects on wider ecological interactions across the site.
- A passive hydrophone array will be deployed to monitor usage of the site by vocalising marine animals and understand potential displacement effects on European Protected Species.
- A mobile fisheries acoustic echosounder survey will be undertaken to investigate fisheries biomass and displacement effects across the wider Fall of Warness site.
- Passive acoustic surveys will be conducted to assess the broad-spectrum acoustic impact of the O2.X at different operating conditions and power production modes.

Under WP9 EMEC will produce the following project deliverables related to the scope of environmental monitoring:

- D9.5: Design specification for Integrated Environmental Monitoring System
- D9.6: Integrated Environmental Monitoring System performance report
- D9.7: Environmental monitoring report

This document presents the IEMS design specification for Deliverable D9.5.

1.2 Aim and objectives

The aim of this deliverable is to present a set of requirements to inform the design, build and deployment of the IEMS, which is proposed as a solution to contribute meaningful data collection of fine-scale interactions and behaviours around operational tidal devices that can subsequently be used to improve collision risk model estimates. The design specification will be achieved through the following objectives:

- **Identify the challenge:** summarise the state of art around collision risk, including the application and limitations of existing collision risk models, and identifying field data requirements to improve their sensitivity.
- **The pathway to a proposed solution:** identify the specific monitoring objectives and FORWARD2030 market uptake innovation targets the IEMS should achieve, summarise lessons learnt from integrated monitoring platforms developed to date, and how these inform the IEMS design requirements.
- **Present the solution:** covering options and technical specifications for monitoring instrumentation and frame requirements, highlighting the key minimum requirements of the system in its first design iteration. Deployment and maintenance options for the IEMS will be considered, as well options considered for refining system integration and data management following proof-of-concept testing.

2 Collision risk summary

The potential for marine animals to encounter and collide with operational tidal turbines is an active area of research and topic of global interest. Uncertainty and knowledge gaps associated with collision risk continue to present challenges within the consenting process for tidal projects, where precautionary regulatory approaches in Europe and North America have led to conditions placed on licences and permits to minimise collision risk, including operational restrictions (Sparling et al., 2020). Post-installation monitoring conditions required from developers are often time and cost-intensive, and risks generating a data burden which cannot be used to meaningfully inform future decision making (Bennet et al., 2016). The purpose of such monitoring is twofold: first, to improve the knowledge about near-field interactions between marine wildlife and operational devices; and second to collect evidence to validate collision risk predictions made in environmental impact assessments during planning (Sparling et al., 2020).

Tidally energetic sites are of significance to marine predators as foraging hotspots (Onoufriou, 2021). Where marine mammal and seabird populations overlap with tidal energy deployments, direct physical interactions with an operational device have the potential to cause physical injury, with potential consequences at a population level. However, there is considerable lack of empirical knowledge on this risk (Macleod et al., 2011). Such interactions are technically challenging to observe, therefore there has been little evidence collected from real-sea data to determine whether such an impact exists and therefore, many of the ecological consequences of such an event have been mostly implied by expert opinion (Busch et al., 2013). Recent progress to date has been made to advance monitoring instrumentation and techniques that address the technical challenge of capturing meaningful data in harsh marine environments. This has allowed improved understanding of how marine mammal and fish species respond to operational tidal turbines at various spatial scales (Coles et al., 2021). However, while monitoring techniques used to date can detect potential collisions, there is no established system yet to reliably confirm whether a collision has occurred (Coles et al., 2021).

2.3 Predictive modelling: gaps and assumptions

Due to the current lack of *in situ* data, collision risk and related models are used to estimate the likelihood of nearby encounter or direct contact with a turbine by marine mammals (seals and cetaceans), basking sharks and diving birds. All models nevertheless require several input parameters including information on the density of individuals in the area, as well as species size, swimming speed and behaviour. However, uncertainty and variability around species behaviour parameters are currently not accounted for in models. Recent studies have shown predictions of risk are extremely sensitive to assumptions about behavioural parameters that can only be measured around operating turbines, such as avoidance or fine-scale evasive responses, and can lead to a conservative assessment approach that results in an overestimation of collision risk (Joy et al., 2018).

Predictive models further assume that individuals' behaviour is homogenous both in space and time. Several studies have shown that species behaviour varies with the flow speed and tidal cycle. Johnston et al. (2021) demonstrated that black guillemots are predominantly associated with mean tidal velocities slower than the 1 m/s cut-in speed while seal diving behaviour was observed to change with tidal phase, while Band et al. (2016) reported seals diving to the seabed more often during the flood tide than the ebb. Accounting for variation in harbour seal occupancy over depth and tidal flows in revised collision risk estimates by Joy et al. (2018) contributed to an overall reduction in collision risk from 1.29 to 0.125 seals per tidal cycle (90.3%), compared to risk calculated under assumptions of uniform habitat use. Such example studies form part of a growing evidence base that highlights the critical need to include fine-scale data when estimating collision risk.

3 Informing the proposed solution

3.1 Integrated platforms literature review

A literature review of journal publications and grey literature was undertaken to inform a design concept for the IEMS which will collect the required data to address environmental regulatory concern of collision risk and fine-scale interactions with the O2 device. The literature review considered previous applications of optic (video cameras, stereo-camera systems) and active acoustic (echosounders, multibeam sonar and acoustic cameras) instrumentation for species detection and measuring animal behaviours, while discussing common limitations of each technology such as visibility, biofouling, acoustic interference and data volume management. The use of a range of sensors in a compact integrated system approach is increasingly recognised to provide a more inclusive overview of marine wildlife interactions with operational turbines, reducing limitations experienced when using a single sensor technology for detection. Synergistic value can be added to a monitoring campaign when combining data from various sources, such as active acoustics, acoustic doppler current profilers (ADCP), passive acoustics (hydrophones, fish tag receivers), optical underwater cameras (HD and artificial illumination), and machine learning algorithms (Clarke et al., 2021).

Case studies were presented in the literature review for five integrated monitoring platform developments, briefly covering instrumentation configurations as well as the system architecture adopted for each. Each case study focused on the technical challenges and lessons learnt varying from sensor function and electrical integration to planning and operations in challenging high-flow environments. Appendix A: Integrated monitoring platformsAppendix A: Integrated monitoring platforms provides a concise summary of the lessons learnt for each of the five integrated platforms investigated in the case studies:

- Flow and Benthic Ecology 4D platform (FLOWBEC)
- Integrated Monitoring Pod (IMP)
- Adaptable Monitoring Package (AMP)
- High Current Underwater Platform (HiCUP)
- Fundy Advanced Sensor Technology (FAST) Program

This process helped to identify and consider the main technical and operational issues that, without early consideration in the design phase, risks the potential to develop into problems in subsequent phases. Some of the biggest remaining challenges for integrated environmental monitoring platforms include the need to assure durability of sensitive equipment in hostile underwater environments, secure power availability to integrated systems, and develop continuous data collection, storage and analysis methods (Hasselman et al., 2020). Joslin (2019) provided the following universal recommendations in a review of imaging sonars:

1) Monitoring objectives for the platform should be clearly outlined prior to system development to ensure the required capabilities are achieved.
2) The software integration and data processing options may drive the instrument selection process. Without the software in place to perform the data processing, long delays in acquiring useful information from the platform should be expected.
3) The mounting and deployment orientation will have a large impact on the image quality. For this reason, it is important to design flexibility into the overall system to allow for alternative instrument configurations.
4) Proper consideration should be given for electrical isolation, corrosion resistance, and biofouling mitigation to ensure long term performance of the platform.
5) Pre-deployment testing in similar environments with easier maintenance options is essential to avoid costly failures during critical deployments.

3.2 FORWARD2030 innovation targets

As one of the project's three market uptake innovations, the ambition for the IEMS is to advance the state of the art in integrated environmental monitoring systems and progress from Technology Readiness Level (TRL) 5 to TRL 7 by project closure (Table 3.1). Recognising the technical challenges experienced to date with deploying previous integrated platforms in challenging high-flow environments (see Section 3 and Appendix A: Integrated monitoring platforms), the proposed solution should aim to improve operational stability and reliability of data capture in such conditions.

	State of the art	Proposed beyond state of the art
TRL	5 – Partial system validation in a relevant environment	7 – System prototype demonstration in an operational environment
Hardware	Some seabed mounted monitoring systems with multiple data feeds but issues with reliability and connectivity	Highly accessible multisensory monitoring hardware for 24 hours effectiveness, high levels of reliability and affordability

	State of the art	Proposed beyond state of the art
Monitoring	Little meaningful data with regard floating tidal energy and changes on ecosystem dynamics of diving birds, fish, marine mammals	Develop a statistically important dataset of interactions between target species and floating tidal turbine

Table 3.1 State of the art, current and targeted TRL of IEMS market uptake innovation

3.3 Specific monitoring objectives

As commonly reported in the literature, defining clear monitoring objectives is key to ensuring the outcomes of a monitoring campaign is fit for purpose. To address the scarcity of in-situ fine-scale species behavioural data required to inform collision risk models, the following monitoring objectives are provided which will govern instrumentation choice and integration with the O2 device:

1. Improve collision risk predictions and fine-scale behavioural monitoring by gathering multibeam sonar data on marine wildlife in the immediate vicinity of the O2 device and its turbines.
2. Run a HD underwater camera array concurrently to the multibeam sonar to ground-truth acoustic target detections and identify species.

3.4 Proposed solution overview

Based on lessons learnt from previous integrated monitoring platforms and instrumentation, it is recommended that the IEMS be developed in an iterative approach to field test each hardware component and associated software for data processing. This approach allows for review of each stage to identify improvements where necessary, and for gradual interface adjustments to progress a reliable system ultimately for long-term fine-scale behavioural monitoring around the O2.X device.

It is recommended the overall design of the IEMS remains relatively simple, with minimal system complexity in the very initial stages dedicated to hardware and software component testing in waters around the O2 device. Designing the IEMS to deploy from the surface floating O2 device would enable simpler and more cost-effective installation and maintenance logistics, while reducing risks associated with deployments with limited accessibility. In line with the monitoring objectives, directional multibeam sonar and optical camera would be paired on a simple frame that allows for fine-scale adjustments to sensor orientation, to capture the optimal field of view for assessing species behaviour near the turbine rotor blades.

Discussions have been held with Orbital Marine Power and NatureScot early in the conceptualisation phase to introduce the project monitoring objectives and aligning IEMS concept. Particularly through the design phase, close collaboration with Orbital Marine Power is essential to define appropriate mounting options, power supply requirements and marine operations involved in deployment, maintenance and data retrieval, culminating in successful implementation of the IEMS with the O2 device. Engagement with key stakeholders is necessary to ensure the proposed solution will help to address the relevant regulatory concerns.

4 Design requirements

4.1 Multibeam sonar

Multibeam sonar is a type of active acoustic instrumentation that can monitor the occurrence and behaviour of marine wildlife (Williamson et al., 2021, Cotter et al., 2020), maximising the potential for detecting potential rare wildlife encounters with the operational O2 device, particularly during poor visibility conditions which can drastically reduce the utility of optical cameras when used in isolation. Due to commonly reported limitations with underwater camera technology (see Section 4.2), this project aims to develop the multibeam sonar as the lead technological component of the IEMS and provide a case to gradually reduce the industry's reliance on sole use of underwater cameras for collision risk monitoring. Therefore, in line with monitoring objective 1 (Section 3.3) it will be crucial to stage commissioning of the multibeam sonar system to ensure reliable positioning, calibration, continuous operation and data acquisition elements.

Previous research has tested and validated a selection of active sonar systems that could potentially be used as marine mammal tracking systems for the tidal stream energy industry (e.g. Hastie, 2013; Williamson et al., 2017, 2021; Francisco and Sundberg, 2019; Polagye et al., 2020a; Staines et al., 2020; Trowse et al., 2021). A number of commercial off-the-shelf (COTS) multibeam sonars are available that have previously been tested in relevant tidal conditions, revealing benefits and limitations to each model which help identify the most preferable characteristics for the IEMS (Table 4.1).

Sonar	Frequency (kHz)	Field of view (°)	Range (m)	Trigger	Software Dev. Kit	Applications	Benefits / limitations
Tritech Gemini	720	120 x 20	<120	Y	Y	• Vessel surveys • Integrated monitoring platform • SeaGen turbine deployment	• Lower resolution for long range target detection • Compatible with other devices and software • Proven resilience to longer-term marine deployments
Teledyne BlueView	900/2250	130 x 20	<100/ <10	Y	Y	• Vessel surveys • Integrated monitoring platform	• Higher resolution for shorter range, fine scale monitoring • 2250 Hz transducer found sensitive to air bubbles (Trowse et al., 2021)
Kongsberg Mesotech	500	120 x 3, 7, 15, or 30	<150	Y	N	• Vessel surveys • Integrated monitoring platform	• No SDK – external application required to mediate communications between sonar and integrated platform control software
Imagenex Delta T	260	120 x 10	<150	Y	Y	Integrated monitoring platform	• Lowest frequency and therefore functional range • Lower indicative cost of £13,600 (per sonar head; Clarke et al., 2021)
Sound Metric ARIS acoustic camera	• 1200/700 • 1800/1100 • 3000/1800	• 28 x 14 • 28 x 14 • 30 x 15	• <80/<35 • <35/<15 • <15/<5	N	N	OPRC, Verdant RITE turbine deployments	• Highest resolution but at narrower range • More expensive option, costing up to £80k (before integration and deployment costs) • Lacks key features for integration (no trigger/SDK)

Table 4.1 Summary specifications of most relevant multibeam sonars and benefits/limitations (adapted from Joslin et al., 2019)

The Tritech Gemini is reported as capable of reliable detection and tracking of marine mammal species including grey and harbour seals, harbour porpoises, and bottlenose dolphins (Hastie et al, 2013). The use of the Tritech Gemini system has been fully validated with marine mammals and has been shown not to cause overt behavioural responses by marine mammals to the functional equipment (Hastie, 2013). Joslin (2019) recommends the Tritech Gemini 720is and Teledyne BlueView M900/2250 systems as best-in-class COTS sensors for tidal turbine monitoring in the high-energy Minas Passage, as they have demonstrated the most successful use cases. Both systems offer the following capabilities which would be advantageous for incorporation on the IEMS:

- Robust build for deployment in high-energy environments;
- Optional triggers for activating underwater video camera recording and data archival (as triggered by acoustic detections), reducing time and cost-intensive data burdens; and
- Manufacturer-supported software development kits (SDK), which are suitable for platform integration as they allow for customised instrument control and data acquisition (Joslin, 2019).

The Tritech Gemini provides longer range applications with lower resolution requirements, while the BlueView will provide higher resolution at closer ranges. Trowse et al. (2021) further compared the near-surface performance of the Tritech Gemini and BlueView systems at 10 and 50 m swath range. While the BlueView offered the impressive ability to resolve finer scale features of target objects at 10 m, the Gemini demonstrated comparable ability to the BlueView to identify targets and provided a higher average target detection score. At 50 m range, the Gemini was still capable of target detection and tracking though was approximately 50% less effective for target identification (Trowse et al., 2021). Moreover, due to compatibility of the Tritech Gemini with other devices and software it has been selected for integrated multi-instrumentation platforms including the AMP, HiCUP and FAST-Environmental Monitoring System (FAST-EMS) (Appendix A: Integrated monitoring platforms). The Gemini has demonstrated resilience to longer term marine deployments and has been adapted for use with protective titanium underwater camera housings (Clarke et al., 2021).

Due to the scale of the O2 device (maximum hull length 74 m; see Section 4.4 for details), the multibeam sonar model selected must achieve a suitable balance between range and resolution to capture potential marine wildlife presence and movement in the vicinity of the turbine rotors. The Tritech Gemini 720is (Table 4.2) is recommended a potential candidate for incorporation with the IEMS due to its detection capabilities in poor visibility environments, compact size and compatibility with pole mount assemblies (see Section 4.3).

Acoustic specifications	
Operating frequency	720 kHz
Angular resolution	1.0° acoustic, 0.25° effective
Range	0.2 – 120 m
Number of beams	512
Horizontal beamwidth	120°
Vertical beamwidth	20° (tilted down 10°)
Update rate	5 – 97 Hz (range dependent)
Range resolution	4 mm and 8 mm (software switchable)

Table 4.2 Tritech Gemini 720is specifications (source: manufacturer)

Equipment constraints

The main anticipated constraint to using the multibeam sonar in near-surface waters off the O2 device is the potential for signal interference caused by high turbulence and associated air bubble entrainment (Figure 4.1), with scattering of the transmitted acoustic signal in turbulent zones of the water column. It is therefore recommended the IEMS incorporates a mechanism for lowering the multibeam sonar to a sufficient depth to avoid acoustic returns from the surface and reduce exposure to entrained air.

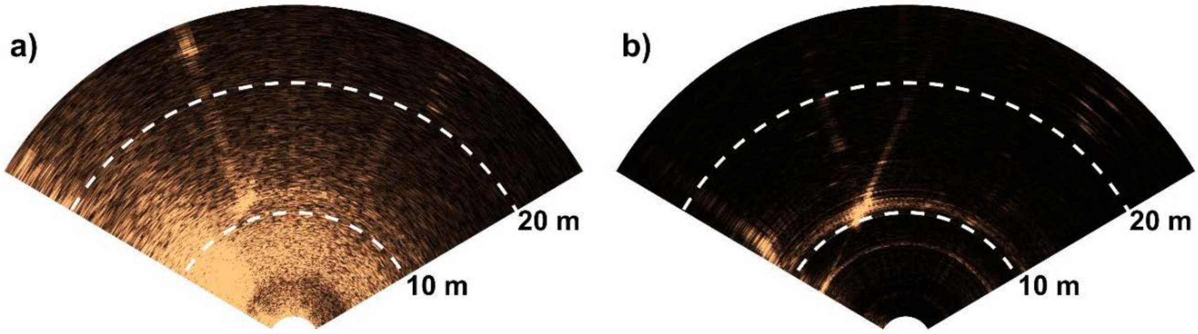


Figure 4.1 Examples of data from a Kongsberg M3 multibeam sonar with relatively high bubble intrusion (a), and relatively low bubble intrusion (b) (Polagye et al., 2020b).

4.2 Optical camera

While multibeam sonar is proven for fine-scale target detection and tracking, identification to species level is not yet possible. Where visibility allows, optical cameras can be used to confirm species and behaviours from an acoustic image and have the advantage of easier manual interpretation by widespread reviewers. In line with monitoring objective 2, an optical camera will be paired with the multibeam sonar on the IEMS with the aim of validating acoustic detections.

Underwater video cameras have previously been used for environmental monitoring around operational tidal turbines, however, to date there have been no studies comparing the performance of different models and specifications in the same challenging, high-flow tidal environment. While Hutchison et al. (2020) compared the effectiveness of underwater video monitoring systems across three separate tidal projects, this was performed on video monitoring data already generated for different objectives and in different locations, therefore specifications between each camera could not be compared. From the extensive range of COTS optical camera systems available, no single model is recommended over others for in-situ monitoring of collision risk, due to universal issues that limit effectiveness for long-term deployment (see below in “Equipment constraints”). The minimum requirements to guide optical camera selection for the IEMS are as follows:

- <10 m operating depth;
- High image definition and colour video to facilitate species identification;
- Low light sensitivity to maximise the period of visibility during daylight hours;
- Field of view: suitable focal length and field of view will depend on IEMS location on the O2 device (Section 4.4); and
- Choice of charge-couple device (CCD) or complementary metal-oxide semiconductor (CMOS) sensor, considering the trade-off that CCD is a more mature technology that gives high-quality, low-noise images, but consumes more power and is more expensive than CMOS. While less expensive, CMOS are lower in quality, resolution and sensitivity.

Comments on the specifications of different camera models used for collision risk monitoring and in integrated monitoring platforms are provided in Table 4.3.

Project / deployment	Camera	Comments on specifications
Orbital Marine Power SR2000 (Fall of Warness, Orkney)	Vivotek FE8174 network dome camera	• Colour video with monochrome vision activated for improved visibility in low-light conditions • Wide-angle (180°) for a wide field of view, however object distortion may occur close to the camera • Internet Protocol (IP) camera sends image data via IP network, only requiring local area network
Sustainable Marine Energy PLAT-I 4.63, (Grand Passage, Nova Scotia)	MacArtney LUXUS compact polyurethane camera	• Lightweight construction • Can be equipped with different lenses for various angles of view (54 or 65°)
Nova Innovation Shetland Tidal Array (Bluemull Sound, Shetland)	Not stated	• High-definition colour video • Incorporated motion detector system to trigger footage retention, however recording could be triggered by false detections (e.g. seaweed snagged next to camera)
AMP integrated platform (University of Washington)	Allied Vision Manta G-507B machine vision camera	• Two high-resolution cameras contained in submersible housings as part of a custom solution for stereo imaging (calibration required) • Monochrome video • Strobe illumination used
FAST integrated platform (FORCE test site, Nova Scotia)	SubC Imaging Sculpin HD subsea camera	• HD colour camera • Software provides for serial control over all functions • Water-corrected wide-angle viewport

Table 4.3 Sample of optical camera applications and comments on specifications

Equipment constraints

Underwater video data quality varies significantly depending on turbine activity, time of day, and site-specific environmental conditions such as weather and turbidity in the water column (Clarke et al., 2021; Polagye et al., 2020a). Recording is restricted to daylight hours, as while the use of artificial lighting would capture potential interaction events over a 24-hour cycle, lighting may have adverse effect on marine animals by influencing behavioural changes and attracting species closer to the turbine (Joslin et al., 2014). Where visibility is poor or monitoring runs continuously overnight, acoustic detection and tracking would continue to be possible using the IEMS multibeam sonar component. Furthermore, biofouling on an underwater camera lens port requires regular maintenance otherwise can result in an unusable video monitoring dataset (Figure 4.2). Preliminary testing of the IEMS and its components are expected to last for 15 days, where at minimum any marine growth should be cleaned upon recovery (further details on IEMS maintenance is provided in Section 4.4). Section 4.5 recommends antifouling strategies beyond cleaning to support longer-term performance.

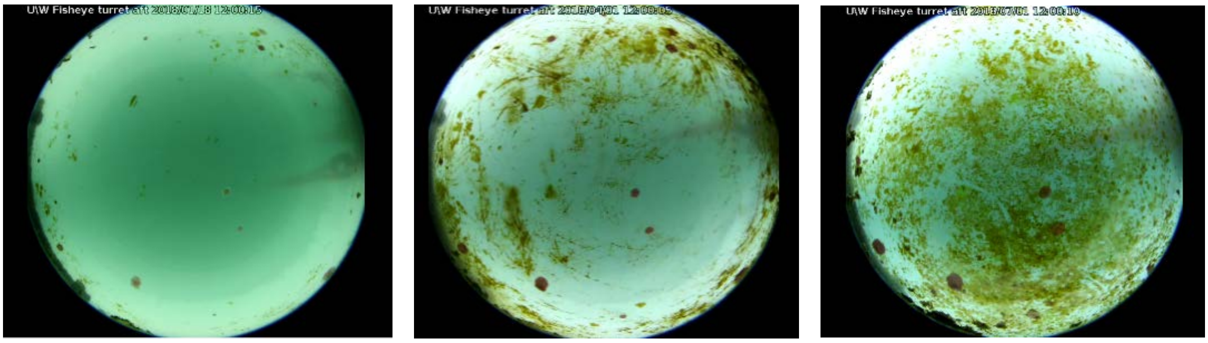


Figure 4.2 Demonstration of biofouling on SR2000 nacelle camera lens (right to left: 18 Jan, 1 April, 1 July). Lenses were cleaned roughly once per month

4.3 Instrumentation frame requirements

Directional sensors such as active sonar and optical cameras rely on accurate positioning when incorporated into an integrated system. The instrumentation frame is driven by the requirement for a structurally simple and adjustable frame, upon which a multibeam sonar and an optical camera can be easily accessible and oriented to capture the O2 turbine rotors within the sensor field of view (FOV), as represented in Figure 4.3. To mitigate any near-surface acoustic interference potentially masking wildlife targets on the multibeam sonar (see Section 4.1), it is recommended the instrumentation frame is extendable to allow equipment to be lowered to an optimal depth.

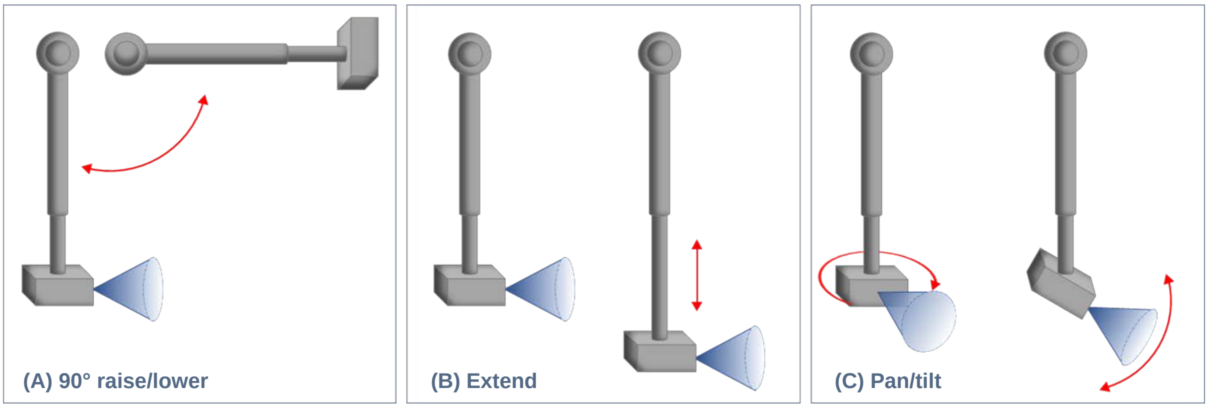


Figure 4.3 Suggested manoeuvrability of IEMS instrumentation frame

Basing the IEMS support frame off over-the-side deployment poles used on survey and research vessels would be advantageous in facilitating low-cost deployment, maintenance and recovery of monitoring equipment. For example, Trowse et al. (2021) configured a vessel pole mount to submerge multibeam sonar and camera equipment to approximately 1 m depth, for studying the comparative performance of Tritech Gemini and BlueView multibeam sonars. Sonar pan and tilt could be adjusted before lowering the pole and fixing into a position where the top of the sonar FOV extended parallel to the surface and downward at a 20° angle (Figure 4.4). It was reported, however, that the pole required strengthening to withstand strong tidal flow with minimal vibrations before data collection, and such flows along the pole mount and vessel hull exposed sonar equipment to signal interference by entrained air (Trowse et al., 2021). Tests using pole-mounted sonar equipment off Sustainable Marine Energy's PLAT-I tidal platform experienced similar stabilisation challenges in high flows of Grand Passage, Nova

Scotia (Sanderson et al., 2019), where streamlining the pole was considered for future iterations to reduce drag forces.

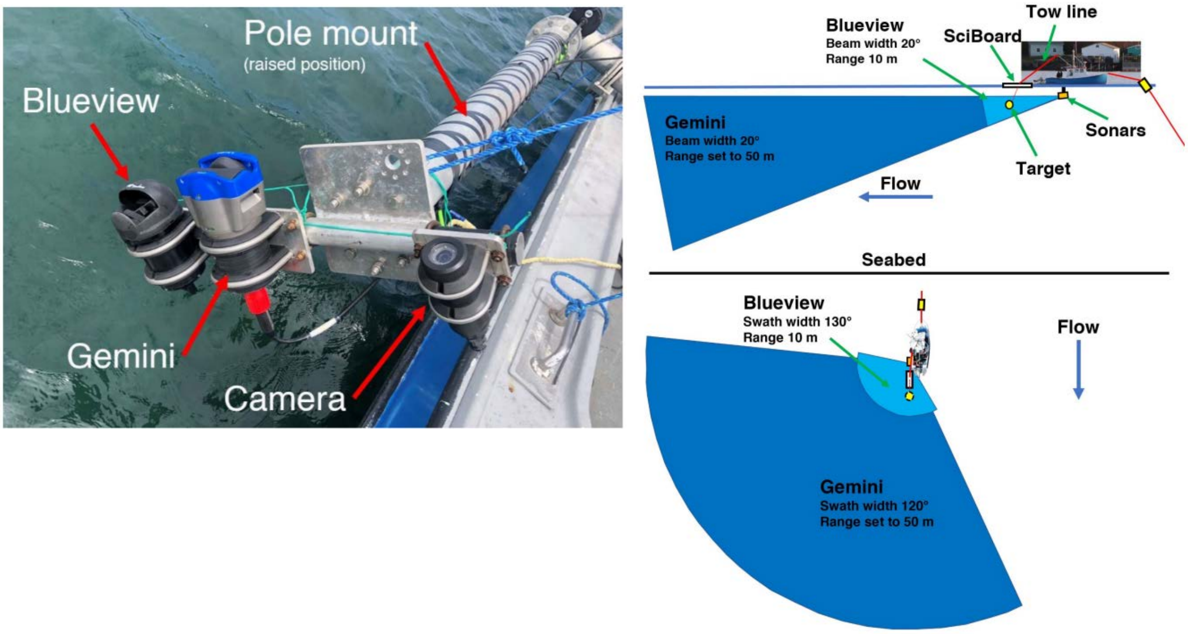
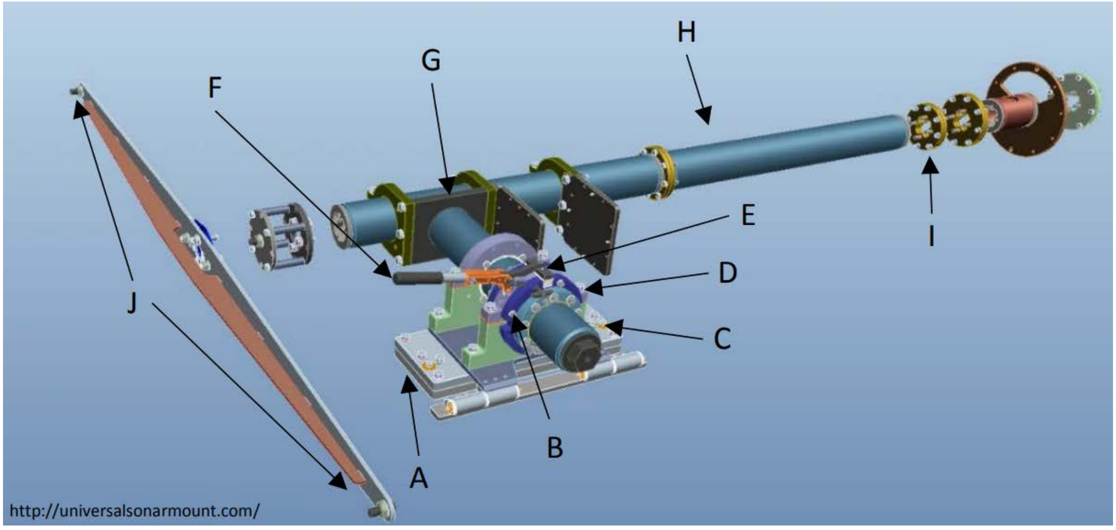


Figure 4.4 Vessel pole mount and sonar orientation (Trowse et al., 2021)

EMEC will collaborate with Orbital Marine Power to identify a custom solution that can be safely mounted on the O2 at a predetermined location, either through fabrication or selecting a suitable COTS vessel deployment pole with components that are manufactured to consistently lock the multibeam sonar into the same survey position (Figure 4.5). Different COTS pole configurations are available depending on the pole requirements, however, modifications to mounting components would be required for the novel purpose of attaching to the O2 tidal structure.



A	**Welded sub-plate and base plate:** secured to the boat and base plate
B	**Carriage bolts**: placed through base unit to prevent the pole from pivoting while in transit
C	**Hinge plate**: bolted to base plate at hinge, allows the mount to hinge into the boat
D	**Base unit:** bolted to hinge plate, holds X-pole in place
E	**Breakaway block:** prevents pole from pivoting during surveying
F	**Breakaway lever:** manually releases breakaway block so pole can pivot
G	**X-pole:** connects Z-pole to base unit
H	**Z-pole:** bolted to sonar mounting frame, held in place by X-pole via braces, cables run down centre of pole
I	**Flange kit:** attaches Z-pole to sonar mounting frame
J	**GPS mount:** bolts to base unit

Figure 4.5 Vessel deployment pole components (example from Universal Sonar Mount, adapted from AAMT, 2017)

4.4 Deployment and maintenance requirements

The IEMS instrumentation frame should be mounted onto the O2 device in a location that allows the multibeam sonar and camera FOV to be positioned toward the turbine rotors, as the key area of interest for collision risk (Figure 4.6). To sample the maximum volume of water, the multibeam sonar transducer should be placed as far back from the area of interest as possible, taking into account the sonar model's effective range for object detection (for example, the effective range of the Tritech Gemini 720 is reported as up to around 50 m for marine mammals; Hastie et al., 2019). Orbital Marine Power will lead the collaborative work with EMEC to identify a suitable and safe mount location which allows for personnel to hand lower/raise the instrumentation frame and subsequent recovery of attached sensors. It is suggested narrowing the potential location of the IEMS to alongside the 74 m length hull of the O2 (Table 4.4) may be most suitable for safe personnel access and desired sensor orientation.

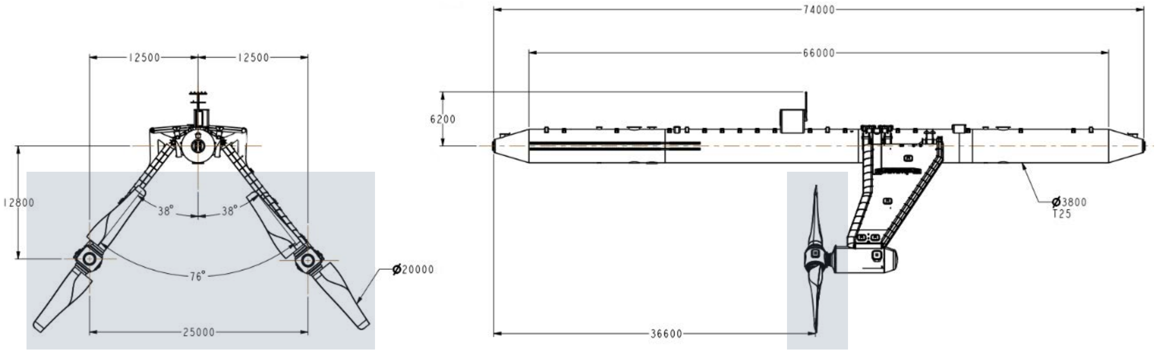


Figure 4.6 Schematic of the general layout of the O2 device with legs down, showing the indicative area of interest for IEMS sonar and camera FOV (grey) (adapted from Orbital Marine Power, 2018)

Device characteristic	O2	O2.X
Maximum hull length	74 m	80 m
Diameter of hull tube	3.8 m	3.8 m
Depth to uppermost rotor tip during operation (rotors extended)	3.2 m	3.2 m
Maximum depth to bottom rotor tip (deepest point) during operation	23.2 m	27.2 m
Maximum depth of platform below waterline	2.3 m	2.3 m
Height of hull tube exposed above the water surface	1.5 m	1.5 m
Maximum rotor diameter	20 m	24 m
Maximum rotor swept area	2 x 314 m^2	2 x 452 m^2

Table 4.4 Summary of O2/O2.X design parameters (Orbital Marine Power 2018; 2021)

Stored within the cylindrical superstructure of the O2 is the main electrical equipment, auxiliary systems and hydraulics. A resilient power supply is crucial to prevent faulty sensor data feeds and consequential gaps in data collection over each survey campaign. EMEC will consider with Orbital Marine Power the power requirements of the IEMS and the potential for powering the IEMS by running sonar and camera cables to internal power supplies within the O2 superstructure. This internal space would also be advantages to locate localised data storage from which data can be recovered after each survey campaign.

The O2 is fundamentally designed for ease of access and inexpensive maintenance, in which personnel can be transferred from a small vessel onto the hull of the device to conduct scheduled and unscheduled maintenance operations (Orbital Marine Power, 2018). Once onboard, personnel can enter the hull and access the majority of equipment. It is recommended that any activities involving the IEMS are paired with existing routine operations to minimise as far as possible the cost and complexity associated with IEMS maintenance operations.

As recommended by Polagye et al. (2020a), a full formal deployment and maintenance checklist will be developed for operations to ensure no potential sources for sensor malfunction or damage are overlooked. It is envisaged that in the beginning, the minimum period of deployment and recovery of the instrumentation frame will be approximately 15 days, to conduct preliminary data collection trials over the full spring tide cycle. General maintenance tasks may include the following upon recovery (but are not limited to):

- Ensuring the sensors are switched off: the multibeam sonar unit should not be operated out of water for extended periods, due to the risk of damage to internal electronics from overheating;
- Rinsing the components thoroughly with freshwater;
- Cleaning off any marine growth;
- Checking for signs of obvious damage, leakage, wear or corrosion, including cable connectors;
- Recovering data;
- If using batteries, charging batteries when not in use;
- Greasing the frame hinge fitting quarterly; and
- Where removing sensors for extended periods: ensuring they are thoroughly dry and protective covers are in place before storing.

A key operational constraint is the requirement to deploy and recover the IEMS during periods of slack tide due to otherwise potentially overwhelming drag forces in the Fall of Warness. This emphasises the importance of ensuring the instrumentation frame and its mount are suitably stabilised to withstand the flow with minimal vibrations.

Through iterative development including incorporation of antifouling measures to prevent overgrowth on sensors (Section 4.5), it is anticipated the IEMS will gradually withstand longer deployments over several months. However, it is recommended that future iterations of the IEMS should be designed to be fully maintained at intervals no longer than six months. While Polagye et al. (2020a) reported no critical sensor failures have occurred during integrated Adapted Monitoring Package (AMP) deployments, problems such as corrosion at dissimilar metal interfaces on manufacturer-supplied equipment have been developed over their longest deployment (over 200 days). While emerging engineering systems and antifouling measures may extend endurance of the IEMS, it is considered critical to design the system for recovery and repair, particularly following extended deployments in challenging high-flow environments.

4.5 IEMS design progression and further integration

Following early-stage sensor commissioning and short-term data collection trials to inform software and data processing protocols, it is recommended that the functionality of the IEMS continues to be built progressively to improve fine-scale wildlife tracking capabilities and performance for long-term deployments. Elements to be considered in the IEMS design progressions, which may occur beyond the FORWARD2030 project, are presented in the following section.

Stereo-acoustic arrangement for three-dimensional tracking

At present there is little evidence on the three-dimensional distribution of marine wildlife in tidally energetic habitats, with few studies demonstrating localisation and 3D acoustic tracking of targets around operational tidal turbines (Gillespie et al., 2020; Gillespie et al., 2021). An individual multibeam sonar only provides location and tracking information in two dimensions, however studies have emerged demonstrating the novel application of dual sonars to extract 3D information in relevant high-flow environments (Hastie et al., 2019). Increasing the ensonified area may increase the potential for identifying evasive behaviours.

A previous study by Sparling et al. (2016) was conducted to test the optimal approach for tracking marine mammals in 3D. Acoustic data was collected using two Tritech Gemini sonars deployed using a custom-built sonar mount which allowed horizontal and vertical orientations of each sonar to be modified in the field (Figure 4.7). The sonar mount was attached to a boat-based deployment pole and lowered from the side of a 7.5 m aluminium vessel. Data were stored onto external HDDs using a laptop PC located in the cabin of the vessel. Two methods of 3D tracking were trialled; one where the sonar swathes were mounted in a perpendicular orientation and one where they were mounted in an offset parallel orientation. To calibrate each technique, an inflatable vessel manoeuvred to a range of between approximately 20-40 m from the sonar and a grey seal carcass (1 m in length) was deployed underwater from the vessel using a custom-built harness and a 50 m rope. An OpenTag depth logger was attached to the seal to calibrate the depth estimates made using the sonars.

It was concluded that while the perpendicular technique is relatively straightforward compared to the horizontal approach, detectable marine mammal movements will be limited to one side of the turbine which will either be upstream or downstream depending on the direction of the tide, given that the most effective location to deploy dual sonars in the perpendicular orientation would be upstream or downstream of the turbine (Sparling et al., 2016). The opposite side of the turbine will always be masked by the turbine itself. The horizontally mounted sonar system (Figure 4.7) is analytically more complex but offers the advantage that it can be located to the side of the turbine which should allow the 3D movements of individual seals to be measured both upstream and downstream of a tidal turbine. It is, therefore, proposed that the offset parallel orientation provides better data to track seals around an operating turbine.

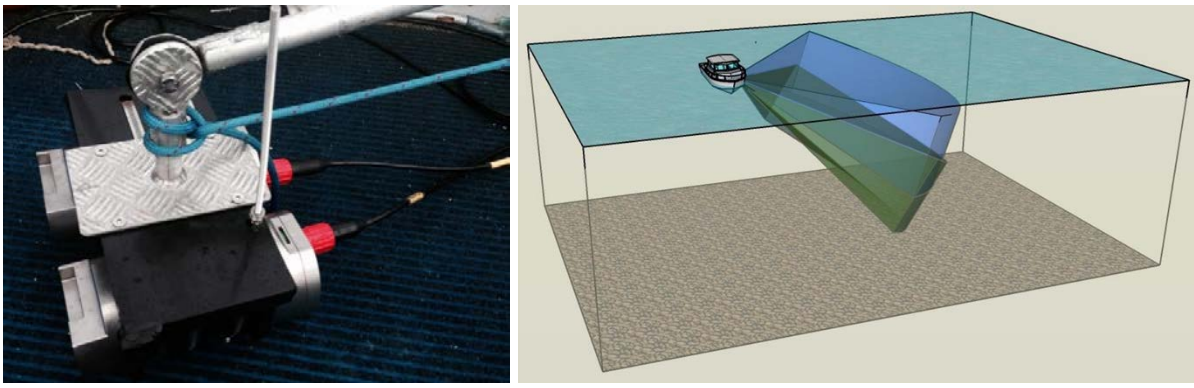


Figure 4.7 Left: Gemini sonar mount, where pivots on the pole allowed for moving horizontal and vertical angles of each sonar. Right: schematic of the acoustic swathes (shown by the blue and green polygons) when the sonars were deployed from the research vessel in a parallel orientation; the sonars were offset by an angle of approximately seven degrees (Sparling et al., 2016)

To test the capabilities of the offset parallel orientation to track the 3D movements of live harbour seals in a tidally energetic location, data were collected Kyle Rhea, a tidally energetic channel on the west coast of Scotland that had previously been shown to have high densities of harbour seals. Using this method, seals were easily identified as highly localised patterns of temporally persistent, high intensity pixels in the sonar images. Based on the results of this study, it was proposed that the offset parallel orientation is used to track seals around operating turbines, with the following key pieces of information required to convert locations in 'sonar-space' to 'turbine-space':

- Relative height of the sonars relative to the turbine nacelle: recommended to be obtained via detailed information on the seabed depths and accurate micro-siting of the sonar platform during deployment;

- Rotation of the sonars in the vertical (yaw) axis: recommended to be obtained via accurate micro-siting of the sonar platform during deployment and can potentially be confirmed from sonar data (imaging the turbine) during installation; and
- Rotation of the sonars in the pitch and roll axes: where a pan and tilt mechanism with an integrated 3D accelerometer/magnetometer is recommended to level the sonars in these axes.

Camera system: array and triggered recording

Due to the scale of the floating tidal structure, camera selection for collision risk monitoring objectives must consider the trade-off between focal length and field of view. While the IEMS instrumentation frame is proposed to be kept simple with a single multibeam sonar and optical camera pairing, the future deployment of additional cameras to view the turbine rotors from different angles would increase the area of coverage around turbine rotors to capture potential evasion behaviours. Furthermore, errors associated with locating seal targets in the vertical plane using a dual multibeam sonar system suggest that collisions may not be reliably confirmed (Sparling et al., 2016), which could be mitigated by having additional cameras mounted to the device (with appropriate antifouling strategies in place).

Reliable detection of wildlife presence and behaviours around an operational tidal turbine requires continuous data acquisition over long periods of time (on the order of days to years) to address environmental regulatory concerns. The use of multiple instruments in an integrated monitoring system has the potential to generate unmanageable volumes of data, termed “data mortgage” (Hasselman et al., 2020). To mitigate the data burden anticipated from longer-term IEMS deployments, it is suggested that IEMS optical and acoustic sensors are further integrated to achieve video data archival triggered by sonar detections. Polagye et al. (2020a) implemented sonar data archival triggered by targets present in multibeam sonar data using manually tuned thresholds for size and intensity. While a relatively high number of false positives were reported for this approach (non-biological targets such as sonar artifacts and backscatter from entrained air resulted in over 40% of triggers), the volume of data was reduced by an order of magnitude compared to continuous archiving (Polagye et al., 2020a).

Antifouling system

During long-term deployments beyond several weeks to months, direct biofouling of sensor equipment and surrounding growth significantly affects the ability to extract useful information from the dataset. The proposed IEMS concept is advantageous as the instrumentation frame allows for easy recovery of sensors to clean off marine growth. It is recommended this task is paired with routine maintenance operations to minimise maintenance costs.

However, where environmental conditions prevent safe access to the O2 or future additional imaging sensors are mounted on permanently submerged locations on the O2.X device, a suitable antifouling strategy should be considered to ensure a clear field of view is maintained. Several antifouling options have previously been tested including the use of mechanical wipers on optical equipment, as well as non-toxic coatings, UV lights, or highly concentrated zinc oxide paste for other sensitive components (Figure 4.8). For less sensitive components, copper or vinyl tape may be used to coat surfaces to inhibit growth or easily remove biofouling (Polagye et al., 2020a; Hasselman et al., 2020). Frequency of actuation and power requirements should be considered where wipers and UV lights are planned, for example Polagye et al. (2020a) reports actuation of the antifouling wiper and UV light system every 30 min drew approximately 6.5 W and 2.5 W respectively.

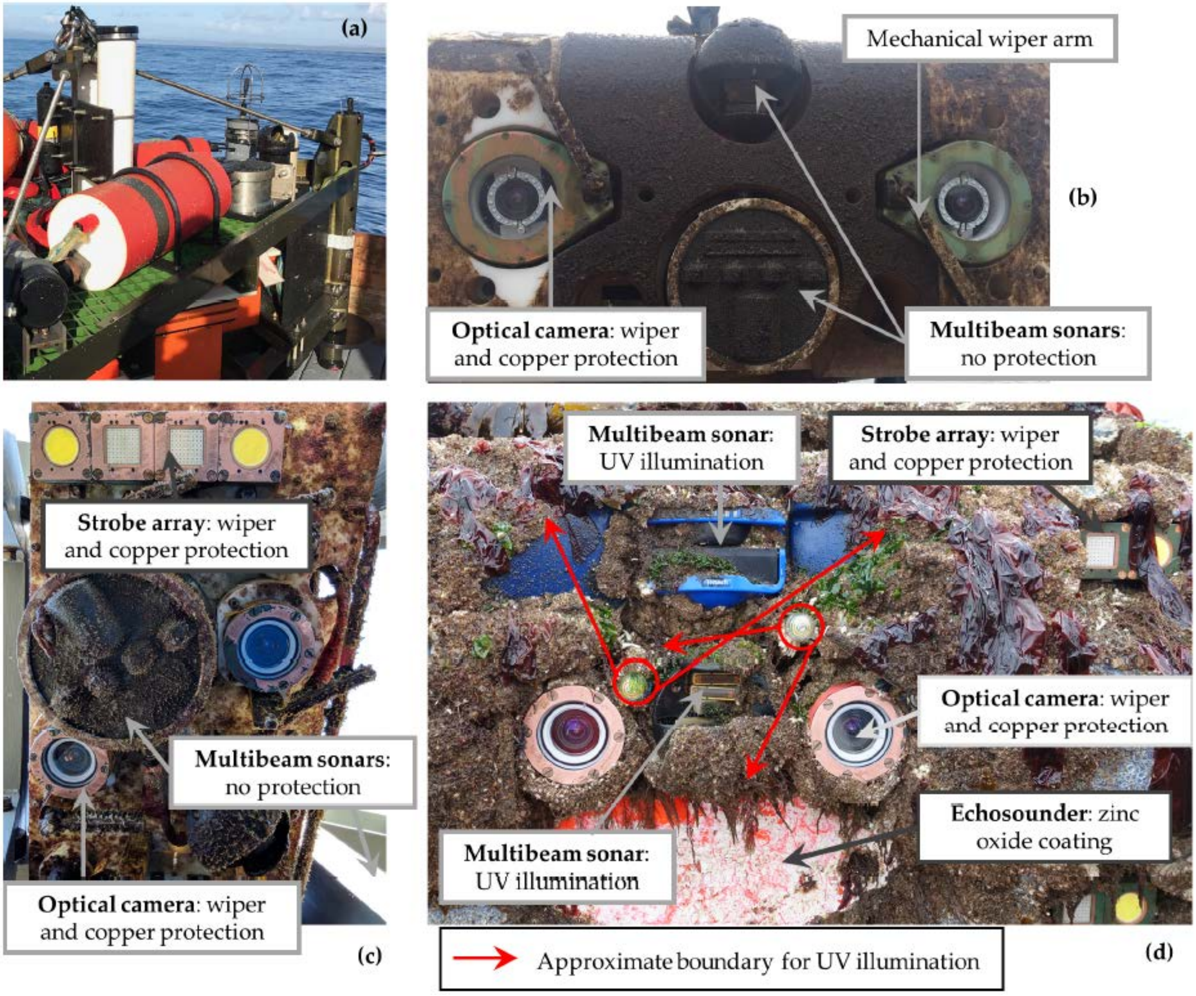


Figure 4.8 Biofouling mitigation measures demonstrated on various AMP deployments: (a) AutoAMP: 44 day at 70 m—negligible fouling, (b) MSL-1: 77 days at 8 m depth— limited fouling, (c) WAMP: >200 days (system in water longer than operated) at 2 m depth—moderate fouling, and (d) MSL-2: 118 days at 7 m depth— heavy fouling (Polagye et al., 2020a)

Data management plan

While preliminary testing of the IEMS will trial software and data processing protocols, lessons learnt from this stage should feed into a data management plan that provides a comprehensive view of how all data generated will be stored, processed and transmitted to end users. The data management plan should be guided by the monitoring objectives actively maintained to ensure any alterations to the monitoring programme are reflected in the plan, and that data generated is fit for purpose. The plan should be developed with input from Orbital Marine Power and IT engineers to devise a feasible data architecture that will prevent potential future cost and time associated with complexities in acquiring, transmitting and handling data.

5 Summary of requirements

The FORWARD2030 project aims to deliver the IEMS as a proposed collaborative solution to the technical and operational challenges of monitoring of fine-scale species interactions and behaviours around floating tidal devices, and to contribute meaningful data which can be used to improve collision risk model estimates. This document has presented a set of requirements drawn from recommendations communicated in the literature to inform the design, build and deployment of the IEMS. The design specification has examined the minimum requirements for both acoustic and optic sensor components, a pole mount-style instrumentation frame, as well as for deployment and maintenance operations. It is strongly recommended the IEMS is developed in an iterative approach to field test each hardware component and associated software for data processing, and to subsequently feed lessons learnt into interface adjustments in future iterations of the IEMS to progress overall reliability of the system for long-term fine-scale behavioural monitoring around floating tidal turbines. Minimum requirements and areas of design progression are summarised in Table 5.1 below.

Minimum requirements	Design progression / further integration
Multibeam sonar	
• Sufficient resolution to detect and track marine wildlife targets up to around 50 m • Robust build that is stable in high-flow environments • Compatibility with pole mount assembly • Selected model to include trigger option and software development kit	• Incorporating a second multibeam sonar with offset parallel orientation to develop 3D tracking capabilities • Incorporating trigger mechanism to activate underwater video data archival • Protective antifouling strategy for long-term deployment such as UV illumination • Acoustic data processing protocols incorporated into data management plan
Optical camera	
• <10 m operating depth • High-definition colour video with appropriate low light sensitivity • Suitable focal length and field of view, depending on suitable IEMS mount locations on O2 • CCD or CMOS sensor	• Additional cameras to increase field of view to better confirm potential collision events or evasion behaviours • Integration of trigger mechanism from multibeam sonar • Protective antifouling strategy for long-term deployment (e.g. mechanical wipers, copper panels, UV lights) • Video data processing protocols incorporated into data management plan
Instrumentation frame	
• Simple: based off over-the-side vessel pole mounts • 90° swing mechanism to submerge equipment, lock into place to maintain multibeam sonar position • Adjustable: extend length, pan and tilt • Reinforced to withstand high tidal flow	• Further streamlining, drag force reduction, and other necessary adjustments based on operational experience
Deployment and maintenance	

Minimum requirements	Design progression / further integration
• IEMS mounted with suitable view of turbine rotors, as area of interest for collision risk • Accessible surface location which allows for manipulation of pole and sensor recovery • Resilient power supply with access to dry interior for localised data storage • All post-survey maintenance tasks to include cleaning, checking components for damage, leakage, wear or corrosion, and data recovery	• Maintenance intervals no longer than six months

Table 5.1 Summary of IEMS minimum requirements and design progressions

6 References

Aquatic Assessment Monitoring Team (AAMT), 2017. Multibeam sonar mounting protocol. Washington: Department of Natural Resources. Available from: https://file.dnr.wa.gov/publications/aqr_aamt_mbs_mounting_protocol.pdf (Accessed 20/05/2022)

Bennet, F., Culloch, R., Tait, A., 2016. Guidance on effective adaptive management and post-consent monitoring strategies. Report No. RiCORE-D5-2D5-4). Available from: https://tethys.pnnl.gov/sites/default/files/publications/Bennet-et-al-2016.pdf (Accessed 25/05/2022)

Busch, M., Kannen, A., Garthe, S. and Jessopp, M., 2013. Consequences of a cumulative perspective on marine environmental impacts: offshore wind farming and seabirds at North Sea scale in context of the EU Marine Strategy Framework Directive. Ocean & Coastal Management, 71, pp.213-224

Clarke, D.R.K.; Bertelli, C.M.; Cole, E.L.; Jones, R.E.; Mendzil, A.F.; Lowe, C.D.; Griffin, R.A.; Robinson, M.T., 2021. Review of monitoring methodologies and technologies, suitable for deployment in high energy environments in Wales, to monitor animal interactions with tidal energy devices. A report produced by Swansea University and Ocean Ecology for Welsh Government. Available from: https://gov.wales/monitoring-interactions-between-animals-and-tidal-energy-devices-report (Accessed 25/05/2022)

Coles, D., Angeloudis, A., Greaves, D., Hastie, G., Lewis, M., Mackie, L., McNaughton, J., Miles, J., Neill, S., Piggott, M., Risch, D., Scott, B., Sparling, C., Stallard, T., Thies, P., Walker, S., White, D., Willden, R., Williamson, B., 2021. A review of the UK and British Channel Islands practical tidal stream energy resource. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 477, 20210469. Available from: https://royalsocietypublishing.org/doi/10.1098/rspa.2021.0469 (Accessed 26/05/2022)

Cotter, E. and Polagye, B., 2020. Automatic classification of biological targets in a tidal channel using a multibeam sonar. Journal of Atmospheric and Oceanic Technology, 37(8), pp.1437-1455

Francisco, F., Sundberg, J., 2019. Detection of Visual Signatures of Marine Mammals and Fish within Marine Renewable Energy Farms using Multibeam Imaging Sonar. Journal of Marine Science and Engineering 7, 22. Available from: https://doi.org/10.3390/jmse7020022 (Accessed 01/06/2022)

Gillespie, D., Palmer, L., Macaulay, J., Sparling, C., Hastie, G., 2020. Passive acoustic methods for tracking the 3D movements of small cetaceans around marine structures. PLOS ONE 15, e0229058. Available from: https://doi.org/10.1371/journal.pone.0229058 (Accessed 25/05/2022)

Gillespie, D., Palmer, L., Macaulay, J., Sparling, C., Hastie, G., 2021. Harbour porpoises exhibit localized evasion of a tidal turbine. Aquatic Conservation: Marine and Freshwater Ecosystems 31, 2459–2468. Available from: https://doi.org/10.1002/aqc.3660 (Accessed 25/05/2022)

Hasselman, D., Barclay, D., Carvagnaro, R., Chandler, C., Cotter, E., Gillespie, D., Hastie, G., Horne, J., Joslin, J., Long, C., McGarry, L., Mueller, R., Sparling, C., Williamson, B., 2020. Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines. In: Copping, A., Hemery, L., [Eds] OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Available from: https://tethys.pnnl.gov/publications/state-of-the-science-2020-chapter-10-environmental-monitoring (Accessed 20/05/2022)

Hastie, G., 2013. Tracking marine mammals around marine renewable energy devices using active sonar. SMRU Ltd. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/232963/OESEA2_SMRU_tracking_marine_mammals_around_renewable_devices.pdf (Accessed 26/05/2022)

Hastie, G.D., Bivins, M., Coram, A., Gordon, J., Jepp, P., MacAulay, J., Sparling, C., Gillespie, D., 2019. Three-dimensional movements of harbour seals in a tidally energetic channel: Application of a novel sonar tracking system. Aquatic Conservation: Marine and Freshwater Ecosystems 29, 564–575. Available from: https://doi.org/10.1002/aqc.3017 (Accessed 01/06/2022)

Hutchison, I., Tait, C., Sheehy, J., Morgan, P., 2020. Review of underwater video data collected around operating tidal stream turbines. NatureScot Research Report No. 1225). Available from: https://www.nature.scot/doc/research-report-1225-review-underwater-video-data-collected-around-operating-tidal-stream-turbines (Accessed 20/01/2022)

Johnston, D.T., Furness, R.W., Robbins, A.M., Tyler, G.A., McIlvenny, J. and Masden, E.A., 2021. Tidal stream use by black guillemots Cepphus grylle in relation to a marine renewable energy development. Marine Ecology Progress Series, 669, pp.201-212. Available from: https://www.int-res.com/abstracts/meps/v669/p201-212/ (Accessed 25/05/2022)

Joslin, J., Polagye, B., Parker-Stetter, S., 2014. Development of a stereo-optical camera system for monitoring tidal turbines. Journal of Applied Remote Sensing 8, 083633. Available from: https://doi.org/10.1117/1.JRS.8.083633 (Accessed 01/06/2022)

Joy, R., Wood, J.D., Sparling, C.E., Tollit, D.J., Copping, A.E. and McConnell, B.J., 2018. Empirical measures of harbor seal behavior and avoidance of an operational tidal turbine. Marine pollution bulletin, 136, pp.92-106. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0025326X18306222 (Accessed 25/05/2022)

Joslin, J., 2019. Imaging sonar review for marine mammal and fish monitoring around tidal turbines. Report for OERA/FORCE, Pathway 2020.
Available from: https://fundyforce.ca/resources/ea188b39d4994ac05c3d20cd36000d62/Appendix6-2019-Imaging-Sonar-Review-for-Marine-Environmental-Monitoring-Around-Tidal-Turbines-JOSLIN.pdf (Accessed 20/05/2022)

Macleod, K., Lacey, C., Quick, N., Hastie, G. and Wilson, J., 2011. Guidance on survey and monitoring in relation to marine renewables deployments in Scotland. Volume 2. Cetaceans and basking sharks. Unpublished draft report to Scottish Natural Heritage and Marine Scotland.
Available from: https://tethys.pnnl.gov/sites/default/files/publications/SNH-2011-Volume-2.pdf (Accessed 25/05/2022)

Ocean Energy Europe, 2020. 2030 Ocean Energy Vision: Industry analysis of future deployments, costs and supply chains. Available from:
https://www.oceanenergy-europe.eu/wp-content/uploads/2020/10/OEE_2030_Ocean_Energy_Vision.pdf (Accessed 25/05/2022)

Ocean Energy Europe, 2022. Ocean Energy: Key trends and statistics 2021. Available from:
https://www.oceanenergy-europe.eu/wp-content/uploads/2022/03/OEE_Stats_and_Trends_2021_web.pdf (Accessed 25/05/2022)

Onoufriou, J., Russell, D.J.F., Thompson, D., Moss, S.E., Hastie, G.D., 2021. Quantifying the effects of tidal turbine array operations on the distribution of marine mammals: Implications for collision risk. Renewable Energy 180, 157–165.
Available from: https://doi.org/10.1016/j.renene.2021.08.052 (Accessed 26/05/2022)

ORJIP Ocean Energy, 2020. Wave and Tidal Stream Critical Evidence Needs. Available from: http://www.orjip.org.uk/sites/default/files/ORJIP%20Ocean%20Energy%20critical%20evidence%20needs%20document_V2.pdf (Accessed 26/05/2022)

Orbital Marine Power, 2018. Orbital O2 2MW Tidal Turbine Project Information Summary. Marine Scotland. Available from: http://marine.gov.scot/sites/default/files/project_information_summary.pdf (Accessed 01/06/2022)

Orbital Marine Power, 2021, Orbital Tidal Turbines Project Information Summary. Marine Scotland. Available from: https://marine.gov.scot/sites/default/files/berth_3_o2.4_pid_submitted.pdf (Accessed 01/06/2022)

Polagye, B., Joslin, J., Murphy, P., Cotter, E., Scott, M., Gibbs, P., Bassett, C., Stewart, A., 2020a. Adaptable Monitoring Package Development and Deployment: Lessons Learned for Integrated Instrumentation at Marine Energy Sites. Journal of Marine Science and Engineering 8, 553.
Available from: https://doi.org/10.3390/jmse8080553 (Accessed 01/06/2022)

Polagye, B., Stewart, A., Joslin, J., Murphy, P., Cotter, E., Gibbs, P., Scott, M., Henkel, S., Matzner, S., 2020b. An Intelligent Adaptable Monitoring Package. Final Report (No. DOE-UW-0006788-1). Univ. of Washington, Seattle, WA (United States).
Available from: https://doi.org/10.2172/1618442 (Accessed 01/06/2022)

Sanderson, B.G., Adams, M.J., Redden, A.M., 2019. Sensor Testing Research for Environmental Effects Monitoring (STREEM). Final Report to the Offshore Energy Research Association of Nova Scotia. Acadia Centre for Estuarine Research, Technical Report No. 127, 68 pp.
Available from: https://oera.ca/research/streem-sensor-testing-research-environmental-effects-monitoring (Accessed 26/05/2022)

Sparling, C., Gillespie, D., Hastie, G., Gordon, J.C.D., MacAulay, J.D.J., Malinka, C., Wu, M., McConnell, B.J., 2016. Scottish Government Demonstration Strategy: Trialling Methods for Tracking the Fine Scale Underwater Movements of Marine Mammals in Areas of Marine Renewable Energy Development. Scottish Marine and Freshwater Science 7.
Available from: https://doi.org/DOI:10.7489/1759-1 (Accessed 01/06/2022)

Sparling, C., Seitz, A.C., Masden, E., Smith, K., 2020. Collision Risk for Animals around Turbines. In: Copping, A., Hemery, L., [Eds] OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World.
Available from: https://tethys.pnnl.gov/publications/state-of-the-science-2020-chapter-3-collision (Accessed 01/06/2022)

Staines, G., Zydlewski, G.B., Viehman, H.A. and Kocik, R., 2020. Applying two active acoustic technologies to document presence of large marine animal targets at a marine renewable energy site. Journal of Marine Science and Engineering, 8(9), p.704.
Available from: https://www.mdpi.com/2077-1312/8/9/704 (Accessed 01/06/2022)

Trowse, G., Guest, T., Feiel, G., Cheel, R., Hay, A., 2021. OERA Pathway 2020 Program - Field Assessment of Multi-beam Sonar Performance in Surface Deployments.
Available from: https://oera.ca/research/multi-beam-imaging-sonar-performance (Accessed 25/05/2022)

Williamson, B.J., Fraser, S., Blondel, P., Bell, P.S., Waggitt, J.J. and Scott, B.E., 2017. Multisensor acoustic tracking of fish and seabird behavior around tidal turbine structures in Scotland. IEEE Journal of Oceanic Engineering, 42(4), pp.948-965.
Available from: https://ieeexplore.ieee.org/document/7820138 (Accessed 01/06/2022)

Williamson, B.J., Blondel, P., Williamson, L.D. and Scott, B.E., 2021. Application of a multibeam echosounder to document changes in animal movement and behaviour around a tidal turbine structure. ICES Journal of Marine Science, 78(4), pp.1253-1266

Appendices

Appendix A: Integrated monitoring platforms

Appendix table A presents the summary outcomes of the literature review conducted to understand the successes and lessons learned from previous integrated monitoring platforms developed to date.

Platform	Developer/ affiliations	Instrumentation	Technical challenges and key lessons learnt
Flow and Benthic Ecology 4D platform (FLOWBEC)	National Oceanography Centre (NOC); Universities of Aberdeen, Bath, Edinburgh, Exeter, Plymouth, Queens University Belfast and National University of Ireland (NUI) Galway	• Imagenex 837B Delta T multibeam echosounder • Simrad EK60 echosounder • SonTek/YSI ADVOcean Acoustic Doppler velocimeter (ADV) • WET Labs ECO FLNTUSB Fluorometer	• Multiple successful deployments with battery packs and sensor integration, with a ping schedule to avoid interference. • Recovery of an 18-month cabled deployment at MeyGen site in Pentland Firth revealed connection issues had prevented power supply during this period. • Tight timescales and pressure to deploy prevented double checking connections prior to deployment.
Integrated Monitoring Pod (IMP)	EMEC	• Bespoke sonar based on Ultra Electronics Forward Look Sonar (FLS) • Acoustic Doppler Current Profiler (ACDP) • Conductivity, Temperature and Depth (CDT) sensor	• Calibration steps were delayed during commissioning of the sonar. Breaking commissioning into small, manageable steps can ensure small issues do not magnify over time. • Data transmission eventually ceased during deployment, where upon investigation it was found the uninterruptible power supply (UPS) had shut down due to excessive power draw. • Increase cable protection to minimise exposure.

Platform	Developer/ affiliations	Instrumentation	Technical challenges and key lessons learnt
			• Plan for all eventualities when operating in hostile tidal environments, with sensitivity for unexpected weather changes. • Effective communications between all personnel involved and collaboration with the supply chain is key for project success, including considering supplier priorities as this may influence lead times for specialist parts.
Adaptable Monitoring Package (AMP)	University of Washington	Four existing platforms developed with various sensor configurations from the following: • ADCP • Multibeam sonar (BlueView M900-2250; Tritech Gemini; Kongsberg M3) • Simrad WBTmini echosounder • Vemco fish tag receiver • OceanSonics icTalk HF hydrophone • SeaBird ecoBB Optical backscatter sensor • Allied Vision Manta G507B optical camera • Strobe lighting: Xenon and custom LED arrays • Antifouling components: UV lights and mechanical wipers	• Multibeam sonar and optical camera instrument range varied with environmental conditions. Air bubbles generated from strong tidal currents or wave action reduced the effective multibeam sonar range, while there was little to no visibility on optic cameras in stormy conditions. • Parallel software development delayed core progress. • A dissimilar metal combination on the M3 multibeam lead to galvanic corrosion, which was considered a potential issue for future multi-year deployments. • The lack of a formal deployment checklist resulted in the system being put into the water and energized without a vent plug installed, leading to catastrophic flooding of the main electronics housing. • Motion of surface devices may lead to ambiguity of target position in the sonar's "vertical" swath dimension, requiring motion correction.

Platform	Developer/ affiliations	Instrumentation	Technical challenges and key lessons learnt
High Current Underwater Platform (HiCUP)	Sea Mammal Research Unit (SMRU)	• Tritech Gemini 720is multibeam sonars x 2 • Hydrophone • UV-C LED lights (antifouling) • Custom pitch-roll mechanism • Reson TC4015 hydrophones x 4	• Combination of dual sonars with additional sensor technology (optical cameras, rotor movement data) is likely to assist in collision detection. • Small scale turbulent hydrographic features persisted in multibeam sonar data at particular tidal states. • During one deployment, water ingress into one of the subsea connectors prevented operation of one of the sonars, preventing validation of 3D marine mammal tracking techniques.
Fundy Advanced Sensor Technology (FAST) Program	Fundy Ocean Research Centre for Energy (FORCE)	FAST-1: • Custom-built "Vectron"- combining range of ADCP with accuracy of ADV for measurements of turbulence through water column FAST Environmental Monitoring System (FAST-EMS): • Tritech Gemini multibeam sonar with pan-tilt unit • OceanSonics icListen hydrophone x 2 • Northek ADCP • SubC Imaging Sculpin HD subsea camera • MacArtney multiplexer ("mux") FAST-3: • Signature 500 ADCP • Aanderaa sensor array: Doppler Current Sensor, conductivity, temperature, depth, turbidity	• FAST-EMS instrumentation performed well under calm conditions. However, issues with the mux and fibre-optic connections require more work with electrical connectors and data transfer with lengthier subsea cables. • FAST-3 echosounder data was subject to contamination by backscatter from entrained air, masking backscatter from fish. The data cleaning process was found to be extremely time-consuming. • Staff turnover and absence of continuity from project inception to close by a single principal investigator generated confusion about study objectives and timelines for those required to take on the project while underway. • Staff training and time was allotted specifically to processing raw hydroacoustic data for analyses. • Lessons learned during operations provided the team with greater understanding of the need for:

Platform	Developer/ affiliations	Instrumentation	Technical challenges and key lessons learnt
		• ASL acoustic zooplankton and fish profiler (AZFP) • Simrad Wide Band Acoustic Receiver (WBAT)	managing effective and safe simultaneous operations, proper calibration and marine operation methodologies, and development of highly qualified personnel.

Appendix table A Instrumentation and lessons learned from previous integrated monitoring platforms

FORWARD 2030

Project Partners

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