Comparing optical camera and imaging sonar observations of animal interactions with a tidal turbine

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Abstract—**The potential for animal injury or mortality because of collisions with operating current energy turbines remains an important research question with consequences for management of proposed marine energy projects. During a 141-day deployment of a small-scale (1 m^2) tidal turbine, a sensor package including optical cameras and imaging sonars was used to record near-field interactions between animals and the turbine. Over 1000 animal interactions were captured by the optical cameras, including several species of fish, at least two species of diving birds, and harbor seals (*Phoca vitulina*). Both seals and fish were observed in the vicinity of the turbine while it was rotating, and a range of behaviors were captured. Seals and fish were also observed while the turbine was stationary, although the observed behaviors were different. Diving birds were observed regularly, but only during daytime hours and when the turbine was stationary. In this work, we summarize trends in animal behavior with respect to tidal elevation, time of day, and turbine operational state and discuss specific observations of collisions (only observed for fish), evasion (fish and seals), avoidance, and attraction. Previously published analysis focused on optical camera data due to their ability to resolve near-field interactions with the rotor. Here, co-temporal sonar data are used to provide additional context that includes capturing a higher degree of animal presence near the operating rotor than determined in review of the optical data, documenting additional examples of avoidance and evasion behavior using the larger field of view, and providing evidence of predator/prey interactions that may inform collision risk. Based on our experiences and findings we also recommend approaches for future projects seeking to acquire, analyze, and report on similar data sets.**

Index Terms—**Tidal turbine, animals, avoidance, evasion, collision**

I. Introduction

THE feasibility of electrical power generation from current energy turbines in tidal and riverine environments has been demonstrated at grid- and community scales in recent years. Smaller-scale turbines have the potential to support small, at-sea power applications [1], [2] but have not been widely adopted. Regardless of scale, uncertainties remain regarding the environmental impacts of current energy turbines [3]–[5]. One topic of interest is animal behavior in the vicinity of operating turbines and the associated risk and consequences of collision to a range of taxonomic groupings.

Environmental sampling to monitor for collisions is challenging. No individual sensor can adequately meet the spatial and temporal sampling requirements needed to characterize animal interactions with turbines [6], [7]. Active acoustic sensors can generally detect animals at greater ranges than optical cameras, but typically have narrower fields of view along one dimension and lower spatial resolution that can make species-level identification challenging. Furthermore, their range and angular resolutions can make it difficult to interpret interactions in close proximity with a moving turbine. In the near-field of a turbine, optical imaging can provide better resolution when turbidity and light conditions permit if the scale of a turbine is sufficiently small. However, for grid-scale turbines capturing a full rotor with optical cameras from a single vantage point is typically not feasible [8]. Thus, there remain inherent sampling challenges to studying animal interactions with operating turbines [9].

To gather data to inform studies of animal behavior and collision risk, optical cameras and imaging sonars were used to monitor a small-scale (1 m^2) vertical-axis, cross-flow turbine deployed in Sequim Bay, Washington (USA). Due to the small size of the rotor, a single camera pair was able to capture the full rotor and a small area around it, facilitating classification of evasion behavior and collisions. An analysis of optical imagery collected during the 141-day deployment is presented in Cotter et al. [10], which identifies over 1000 interactions between fish, fish schools, birds, and seals with the small turbine captured from data obtained either on a duty cycle or with machine learning models (YOLOv8 [11]) applied to real-time acquisition. Captured interactions were classified according to taxonomic groupings and observed behaviors including avoidance, evasion, and collision. Consistent with Garavelli et el. (2024) [5], these terms are defined as follows:

- Avoidance: An animal avoids the turbine if it responds to the presence of the turbine and moves away at a distance greater than 5x the turbine diameter.

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- Evasion: An animal evades the turbine if it modifies its behavior to avoid collision within 5x the turbine diameter.
- Collision: An animal is struck by a moving component of the turbine.

This work presents another view of the observations described in Cotter et al. [10], by extending the analysis of the animal interactions identified in the optical camera imagery to include the acoustic images. Because the imaging sonars had a maximum range of 10 m or greater, this expands the area over which we are able to observe animal behavior. In addition, comparison between the optical and acoustic imagery allows us to explore the advantages and challenges of integrated sensing using both optical and acoustic sensors. To achieve this, Section II introduces the site, sampling methods, and data; Section III summarizes the results and key findings with comparisons to optical data; and Section IV contextualizes these findings and includes recommendations for future work.

II. Methodology

The vertical-axis, cross-flow turbine considered here, referred to as the Turbine Lander, was deployed in the tidal channel at the entrance to Sequim Bay for 141 days from 18 October 2023 to 7 March 2024. Water depth at the turbine's location was approximately 8 m (mean lower low water) and peak tidal currents exceed 2 m/s [12]. The site is near the Marine and Coastal Research Laboratory (Pacific Northwest National Laboratory), which facilitated high bandwidth, real-time data acquisition from environmental sensors via a short (< 160 m) fiber optic and power cable. Environmental monitoring was performed using an Adaptable Monitoring Package (AMP) [13] equipped with a custom stereo-optical camera system with artificial illumination and three imaging sonars, among other sensors. The imaging sonars (two Teledyne Blueview M900-2250 and one Tritech Gemini 720is) were positioned on the Turbine Lander approximately 1.5 m from the turbine rotor. The Blueviews were oriented 90° away from each other but overlapping approximately 45° at the rotor while the Tritech directly faced the rotor. The Blueviews were operated at 2250 kHz and recorded out to a range of 10 m while the Gemini operated at 720 kHz and recorded data at out to a range of 15 m. During the deployment, the platform was oriented such that the dominant direction of flow on both flood and ebb tides was perpendicular to the orientation of the optical cameras and Gemini. In this orientation, the Blueview imagery captured the area 10 m up and downstream of the rotor. Figure 1 includes a picture of the Turbine Lander with the AMP, which shows the orientation of the sensors, and a more detailed description of the system can be found in [14]. Data were collected using a mix of continuous recording, duty-cycled recording, and data archival when animals were detected in real-time by machine learning models. A full description of the optical sampling and artificial illumination is beyond the scope of this work but is described in detail in [10].

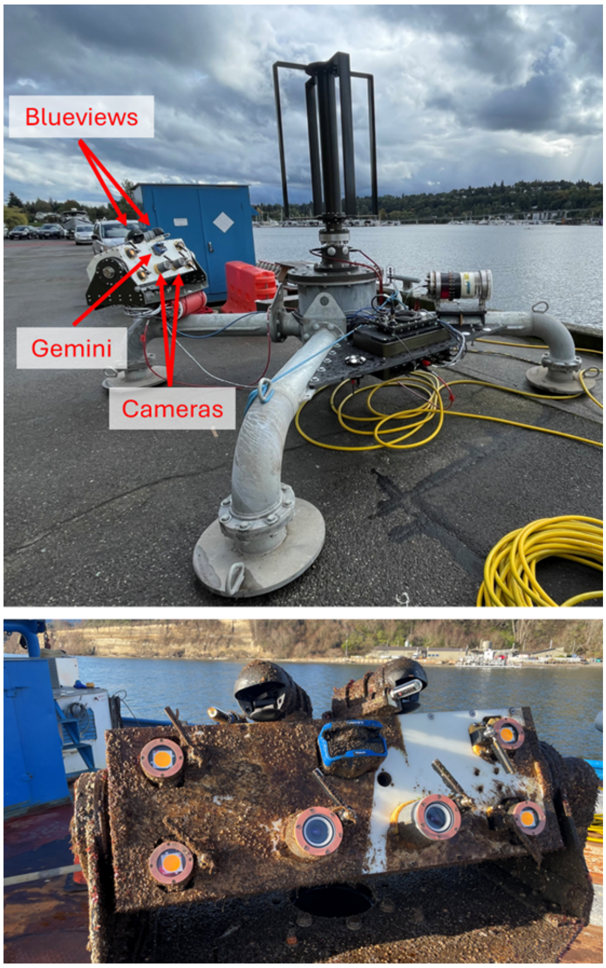

Fig. 1. (top) A picture of the Turbine Lander with the Adaptable Monitoring Package installed on the foundation. (bottom) A post-recovery image of the AMP showing the orientation of the sensors.

Manual review of optical data in [10] identified over 1000 events containing animal interactions with the turbine. Observed animals included diving birds (406 events), seals (92 events), individual fish (524 events), and fish schools (19 events). In this work, we analyze the sonar imagery corresponding to 146 of these events (21 diving birds, 77 individual fish, 9 fish schools, and 39 seals). These events included instances of evasion, collision, and representative observations of all taxonomic groups interacting with the rotor when they did not collide with the rotor or demonstrate evasion behavior. To select events for review, first, a spreadsheet containing detection timestamps, inflow conditions, taxonomic classifications, event types (e.g., rotor state, interaction type), and notes for the optical cameras was compiled. This list was then trimmed to include events corresponding to each taxonomic classification and behavior type, and only included events when recorded optical and acoustic frames rates were 10 Hz or greater. Events that would not be captured by the sonars because the observed animals were outside of the sonar field of view (e.g., interacting with the base of the turbine) were excluded.

The following steps were taken to review each of the 146 selected events:

1) Data from all three imaging sonars units were downloaded and used to create a single, half-

speed video of the event that included the timestamps corresponding to the full event (as inferred from the optical cameras) ± 10 s.

2) All three sonar videos for each event were reviewed along with the optical camera data and notes to identify whether animals were detected by the sonars and the acoustic imagery yielded additional information (e.g., additional animals that were beyond the optical camera field of view).
3) Notes on each video were added to a spreadsheet containing each event and associated metadata.

In total, videos from 70 events were retained (i.e., uploaded to a public repository and used to make figures) as representative of cases of interest. While this data set included cases where the imaging sonar data provided new information about the event, it also included examples in which the sonars provided no clarifying information or the interactions that were observed in the optical camera data were not detectable in the imaging sonar data. The 77 events not retained for further consideration all fell into these latter categories. These videos and associated metadata are available online [15]. For further information about the optically inferred outcomes of events described here see [10].

III. Results

While the focus of this paper is on the sonar data, salient details of the results of optical camera data analysis in [10] are repeated here for context. Diving birds, fish, and seals were all observed around the Turbine Lander, though they exhibited different behavior and trends in presence/absence with respect to the time of day and tidal conditions. Diving birds were only observed during the day and during low flow speeds (<1.1 m/s) when the turbine was stationary. Many of the observed interactions included birds diving to forage on or around the Turbine Lander. Seals were observed more frequently at night than during the day and were observed when the rotor was both stationary and moving. In many cases, the seal did not seem to change its behavior in response to the presence of the turbine (i.e., a seal swam past the system but no other specific behavior was observed). In other cases, we observed seals attracted to, evading, or foraging near the rotor. Individual fish and fish schools were observed near the rotor across all stages of the tide. Over 98% of the fish observed were relatively small (i.e., estimated to be < 25 cm in length with most being much smaller). Observed behaviors included direct interactions with the stationary rotor, ambiguous interactions (e.g., an animal drifting past without moving), evasion, and collision with the moving rotor. Cotter et al. [10] discusses these observations using the optical cameras in greater detail. An example time series of showing all events detected in the optical camera data during a representative period of data collection is shown in Figure 2. While limited in duration, the patterns present in this short time series are generally consistent with the long-term observations in that birds were observed during the day when currents were weak while the other taxonomic groups were identified over a broad range of conditions.

A. Sonar performance and orientation

Due to their orientation and location relative to the rotor, the Blueviews resulted in more compelling imagery than the Gemini. As shown in figures throughout this section, the Blueview imagery has bands of high noise that segment the image into four regions. While these bands can be suppressed using background subtraction, they pose a significant challenge for detection and tracking methods as animals can become undetectable as they pass through these portions of the ensonified volume. Both Blueview units used here are the original M900-2250 models and newer models may be less impacted. While similar artifacts do not exist in data recorded by the Gemini, data had comparatively low range resolution and image quality. This was attributed to how the processing thresholds were set and data interpolation/decimation performed by the AMP. Recent modifications to the AMP software have improved image quality and there remain additional opportunities to further improve the Gemini's integrated sampling capabilities using the Tritech software development kit.

Because we were limited to deploying the monitoring instrumentation on the Turbine Lander structure, the sensors were in relatively close range to the turbine, which ultimately reduced our ability to observe animal interactions with the turbine using these sensors. Because the sonars field of view is approximately 20° in the vertical direction, they only ensonified approximately half of the height of the rotor. Furthermore, because the AMP was placed low on the foundation of the Turbine Lander to increase stability in strong currents, the sensors were tilted upward approximately 30° and primarily ensonified the upper portion of the rotor, which limited detections of animals lower in the water column. As a result, many animals observed in the optical camera data, which captured the entire rotor, did not appear in the sonar data.

B. Individual Fish

Review of acoustic imagery revealed that individual fish were difficult to identify in the sonar data. We attribute this primarily to the presence of plant matter in the water column drifting with the currents. In most of the reviewed Blueview videos there were objects drifting passively with the current that could not be distinguished as plant or animal. While we experienced similar challenges distinguishing fish that were drifting passively with the currents from plant matter in the optical camera imagery, this challenge was more pronounced in the imaging sonar data. In addition to difficulties distinguishing fish, many of the events reviewed in acoustic data did not include an obvious object corresponding to the fish that was observed in the optical camera imagery. However, in many cases, this was likely a consequence of the limited field of view of the sonars.

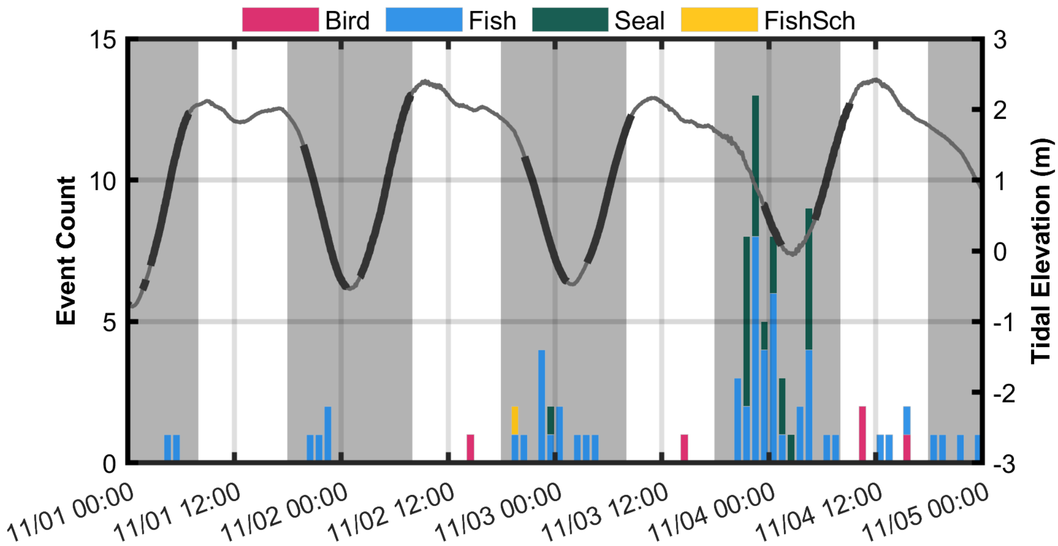

Fig. 2. An example time series of optical detections of seals, birds, individual fish, and fish schools. The dark background patches correspond to the period between sunset and sunrise while the thick portions of the tidal elevation line highlight periods when the rotor was moving. Note that in this example most fish and all seal detections occurred at night. This was not uniformly true in the data set and therefore represents a bias in this subset of observations. Cotter et al. [10] notes that observations of small fish were more commonly observed at night, which we hypothesize is driven by specular reflections of the artificial light aiding in identification.

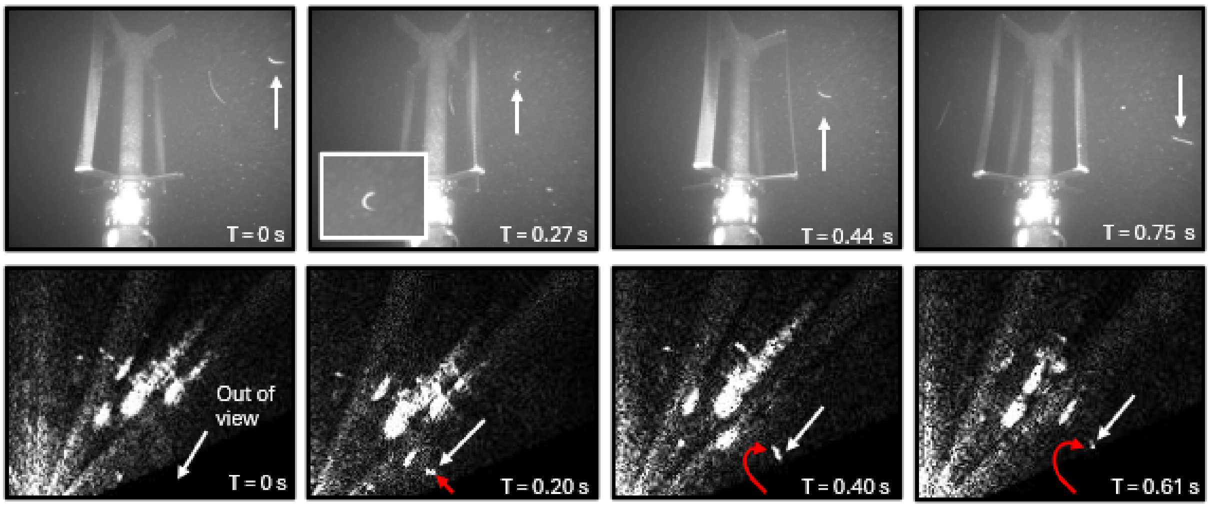

Fig. 3. An example of a fish evading the turbine, which was captured in optical and Blueview images (the Gemini is not included as no distinguishing features were identified). In this sequence, a fish is approaching the turbine (moving with the current) and turns and swims against the current as it approaches the blades. The event was clearly identifiable in the Blueview. White arrows in both images point to the fish and the red arrows indicate the direction of travel. The relative time in seconds from the beginning of the event, denoted by T, is shown in each panel.

Despite the challenges, the imaging sonars did provide useful information about several fish evasion and collision events observed in the optical camera data. For example, in Figure 3, optical images show a fish approaching the moving rotor in the same direction as the current. As the fish approached the rotor, it turned to swim away from the rotor against the currents. This behavior was also observed in the Blueview data. In other examples (not shown) individual fish were observed changing their trajectories to avoid the rotor. In some cases this shift in trajectory was more clearly observed using the acoustic images than the optical data because it occurred upstream of the rotor near the edge of (or outside of) the field of view of the optical cameras.

While some instances of evasion were supported by imaging sonar data, these images did not typically provide information about these events that was not captured in the optical camera imagery, and in some cases, did not contain any information about the event. For example, in several events where fish either collided with or entered the rotor, the fish was difficult to identify in the acoustic images while it was in close proximity to the rotor, despite being clear in acoustic images immediately before or after the event. For example, Figure 4 shows a collision event that was not observed acoustically although the animal was captured approaching and swimming away. In such examples, it is clear from the imaging sonar data that a fish was close to the turbine, but clutter and the resolution of the images make it difficult to infer the outcome of the interaction.

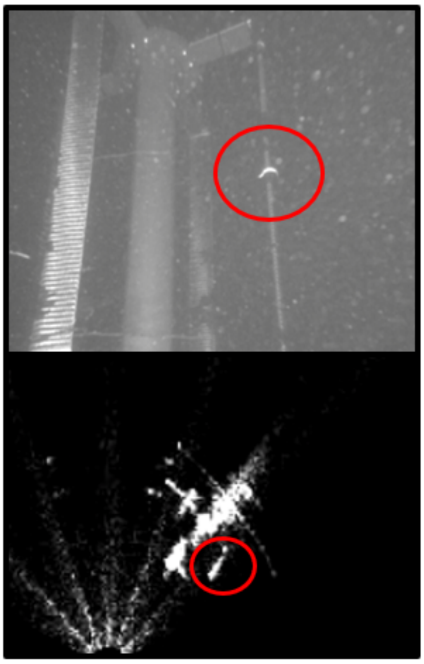

Fig. 4. (top) A collision event showing a fish struck by a moving turbine blade. (bottom) The collision is not visible in the acoustic images, but the fish was captured in frames before and after the event. The optical images show that after the collision the fish exited the rotor and swam towards the AMP.

Larger fish (i.e., > 30 cm) that were identified within the field of view of the imaging sonars were readily distinguishable from most plant matter due to their shape or movement (Figure 5). Thus, if concerns related to collision risk at a given site are driven by larger fish species, active acoustic sensors can be a valuable tool for monitoring and automated data processing would likely be easier to implement than for smaller fish.

C. Fish Schools

Unlike individual fishes, the relative size and movement of fish schools made them easy to detect with the imaging sonars (Figure 6), which were able to provide additional information in support of the optical images. For example, one optical event showed several small fish evading the moving rotor over a period of a few seconds. Acoustic imagery revealed that these fish were part of a much larger school that passed behind the rotor outside of the optical camera field of view (i.e., all fish avoided or evaded the rotor). In another similar event a school of fish avoiding/evading the stationary rotor and but the acoustic imagery revealed that the school was much larger than was evident in the optical images. The acoustics also revealed that a seal was present approximately 8 m away from the fish seconds before the school dispersed near the turbine. Thus, it is unclear whether this behavior occurred in response to the school approaching the rotor, the seal, or a combination of the two. While the total sample size is limited, the reviewed imaging sonar data containing fish schools provide many additional examples of evasion behavior that were not captured by the optical cameras due to their limited sampling range. In fact, the total inferred number of rotor evasion events for individual fishes identified throughout the deployment by Cotter et al. (2026) [10] would increase by a significant factor (order 100%) with the inclusion of examples observed in the limited analysis of imaging sonar data. No collisions between individual fish that were part of fish schools were observed.

D. Birds

Over 400 bird events were identified in optical imagery and most of these events were easily identified in both optical and acoustic images. Species identification was typically possible for birds in the optical camera imagery. Both pigeon guillemots (*Cepphus columba*) and double-crested cormorants (*Nannopterum auritum*) were regularly observed. Cormorants most frequently dove directly to the seabed while guillemots were more often observed swimming at low angle trajectories across the camera field of view. Using the imaging sonars, species identification is more difficult although differences in size, shape, and swimming pattens suggest some degree of discrimination should be feasible. For example, since cormorant trajectories were relatively steep, they were often observed in only a small number of acoustic images while guillemots often remained in the acoustic images for seconds at a time.

Examples of acoustic signatures corresponding to cormorants and pigeon guillemots are shown in Figure 7. In most cases, birds were not identifiable in the sonar images based on their shape alone. Rather, they could be identified based on their diving patterns and the plumes of bubbles left in their wake while swimming [16], [17]. While these characteristics typically made it straightforward to identify birds in the sonar imagery, it was not possible to characterize fine-scale behavior of birds around the turbine rotor. For example, in one optical event, a guillemot swam directly through the blades of the stationary rotor. In a second event, a guillemot swam to the top of the rotor and appeared to pick at biofouling accumulating on the rotor end plates. Neither of these behaviors were distinguishable in the acoustic camera data.

Given that birds were readily identifiable with the imaging sonars, and successful detection and classification algorithms using imaging sonars has previously been demonstrated [18], sonars can play a valuable role in assessing collision risk for diving birds by enabling sampling over a broader area than is possible with optical cameras to facilitate an understanding of the temporal and spatial distributions of animals near turbines.

E. Seals

Cotter et al. (2025) [10] reported 92 unique seal events in the optical camera data. The observations spanned a broad range of behaviors, including swimming around the stationary and moving rotator, foraging around the Turbine Lander, swimming in its wake, and close proximity interactions (within the swept volume) while the rotor was stationary (Figure 8). Several interesting results emerged from analysis of the acoustic imagery. Eleven additional seals were detected in review of the sonar imagery that were not

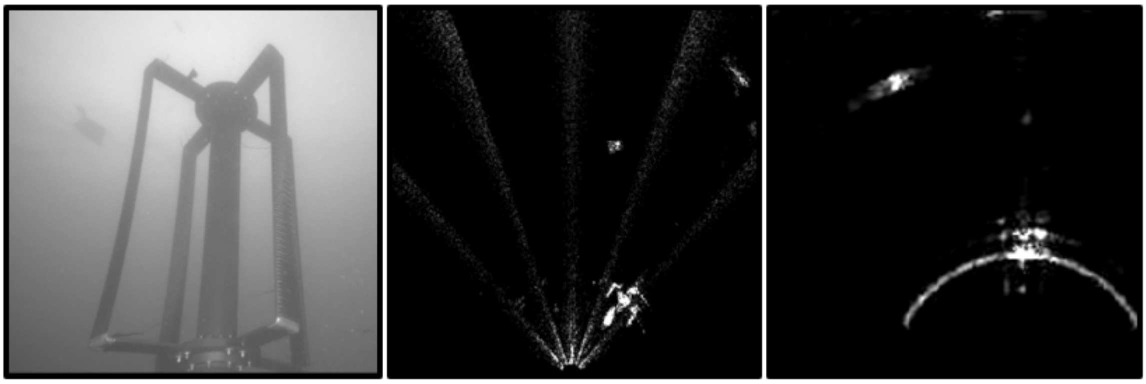

Fig. 5. An unidentified fish, most likely a starry flounder (*Platichthys stellatus*), drifting above the rotor. The fish was clear in both the Blueview (middle) and Gemini (right) images.

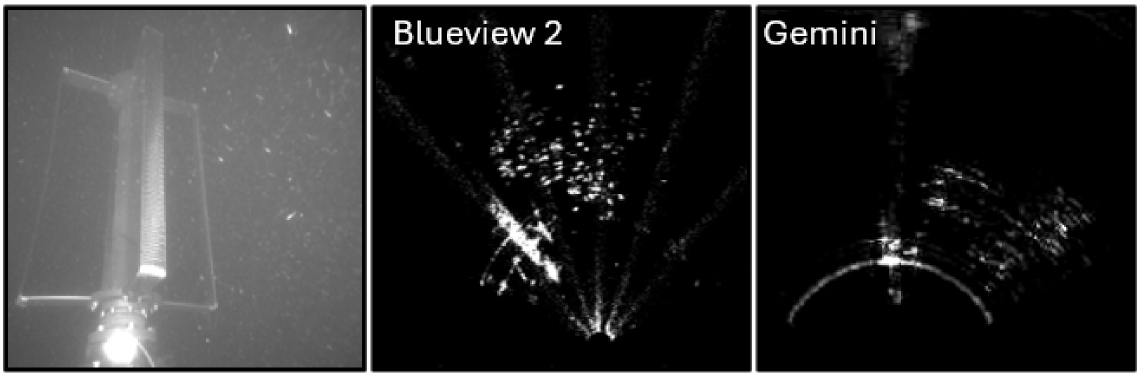

Fig. 6. A fish school recorded on 12 Dec. 2024 at 03:05. Although there are many fish in the optical images, the acoustics reveal the school was larger and dispersed around the stationary rotor as it approached. The acoustics also revealed a seal in the area (not shown) that was not captured by the optical cameras.

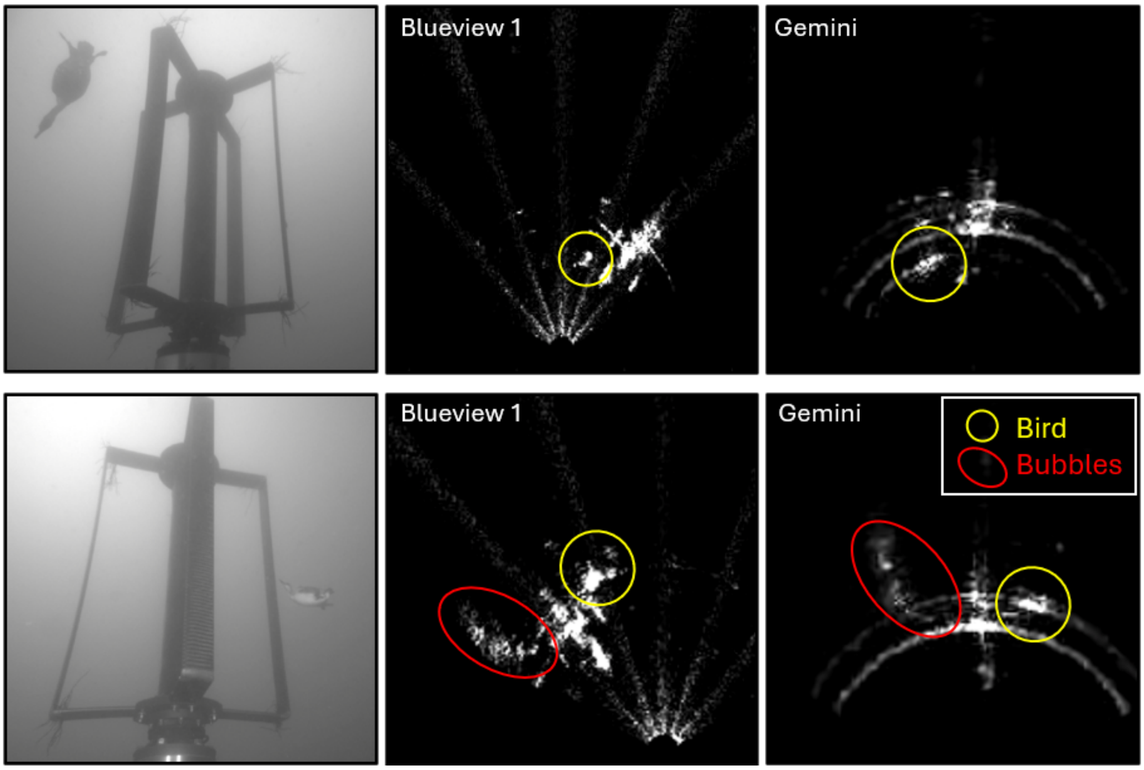

Fig. 7. (Top row) A cormorant diving near the rotor. (Bottom row) A pigeon guillemot near the rotor after swimming around it. A bubble plume from the guillemot is clear on the opposite side of the turbine from the bird.

within the optical camera field of view, which increased the total number of identified seal interactions by more than 10%. Six of these 11 seals that were identified acoustically were present while the rotor was rotating, increasing the total number of seals observations during turbine operations by more than 50%. In addition, we identified seals in the vicinity of the turbine in the sonar data associated with several fish collision and evasions events. In one optically identified fish collision event, the fish swims against the current and into the rotor. Review of the cotemporal imaging sonar data shows a seal in pursuit of the fish just before the collision. This seal was not observed in the optical data. In another cases, a fish that is drifting passively with the current collides with the stationary rotor before swimming away rapidly. The acoustics show multiple seals within a range of approximately 7 m, one of which turns and swims toward the rotor at approximately the same time as the collision. While the presence of the seal and fish collision may be a coincidence in this case, the fact that several other collision and evasion events corresponded with predator/prey interactions suggests this may be an important factor to consider when assessing collision risk.

In most sonar images, the shape of seals was well defined or its size uniquely large among other observed targets. However, this was not always true when seals were directly interacting with the turbine rotor or at close range to the sonar (Figure 8). In event 1 in Figure 8, the optical imagery revealed that a seal swam in the wake of the moving turbine with its head oriented towards the turbine. Stereo-optical processing using the two optical cameras suggests that the seal did not enter the plane swept by the turbine blades, though this was not clear from a optical imagery from a single camera. The imaging sonars also revealed a close encounter, but lacked the resolution to provide further information. The second event in Figure 8 includes a seal interacting with the rotor while it was stationary. The position of the seal in the same vertical “slice” of the water column makes the seal difficult to detect or identify in the acoustic camera imagery.

F. Environmental Factors

Water clarity has clear implications for optical camera detection capabilities, but also has implications for sonar operations. During testing we observed large, and at times rapid (e.g., within ten minutes), shifts in background scattering conditions. These were observed both during periods when the rotor was stationary and when it was rotating. Images presented in previous sections show the rotor and biological targets during periods with relatively low intensity background backscatter. In contrast, Figure 9 shows a period during which high levels of suspended particulate elevated background noise levels and made it difficult to detect the turbine.

A detailed analysis to quantify the fraction of the Blueview data that was impacted by poor signal-to-noise ratios associated with suspended particulate has not been performed, though cursory manual review of the data reveals that it was not negligible. However, we note that the Gemini did not suffer as significantly from decreases in the signal-to-noise ratio attributed to suspended particulate. While some of this may be attributed to the noise floor of the images, we hypothesize that this maybe also be driven by the lower operating frequency of the Gemini. Suspended sediments and other particulate modeled as small spheres will exhibit an f^4 frequency dependence in the Rayleigh scattering regime [19]. This occurs when $\frac{2\pi f}{c}a \ll 1$, where f is the frequency, c is the sound speed of the water, and a is the radius of the particulate. For particulate like suspended sediments, this can mean drastic decreases in scattering as acoustic frequencies are reduced. No specific measurements related to this study are available, but published suspended sediment distributions from a nearby river [20] suggest that the transition to the Rayleigh scattering regime could occur well above 1 MHz. For reference, Cotter and Polagye (2020) [17] contains a more detailed description of the general trade-off between the Blueview and Gemini sonars at the same site (with no turbine present).

IV. Discussion and Conclusions

Environmental monitoring campaigns around marine energy converters should identify the environmental stressors and species of interest early in the process, as this information will inform sensor selection, sensor positioning and orientation, and data processing priorities. This will not only result in the highest-possible quality data, but will facilitate prioritization of data analysis. High-volume data sets require considerable time for quality control and post-processing. Without significant financial resources, it is difficult to review multiple data streams or identify all animals that interact with a marine energy converter. Establishing objectives in advance helps ensure that both sampling and post-processing are aligned with project priorities. For example, monitoring for fine-scale animal interactions (i.e., evasion or collision) might require different sensors and sensor positioning than monitoring for animal presence/absence at a larger scale.

The configuration of the environmental monitoring equipment on the Turbine Lander was ideal for observing fine-scale animal interactions with the turbine with the optical cameras, but suboptimal for monitoring over longer ranges with the imaging sonars. This is because the placement of the imaging sonars was restricted by the size and weight of the Turbine Lander platform and efforts to limit its overturning moment. Ideally, the sensors would have been placed higher in the water column so that they could capture the rotor at normal incidence. In this orientation, animals moving at constant depth would not move in and out of the beam. Furthermore, the sonars would have been placed further from the rotor so that it was fully ensonified by the beam. This would still have resulted in some loss of data in the vicinity of the turbine, but fewer of the animal interactions with the turbine would have been outside of the sonar fields of view. As a result, our emphasis for data analysis was on the optical camera

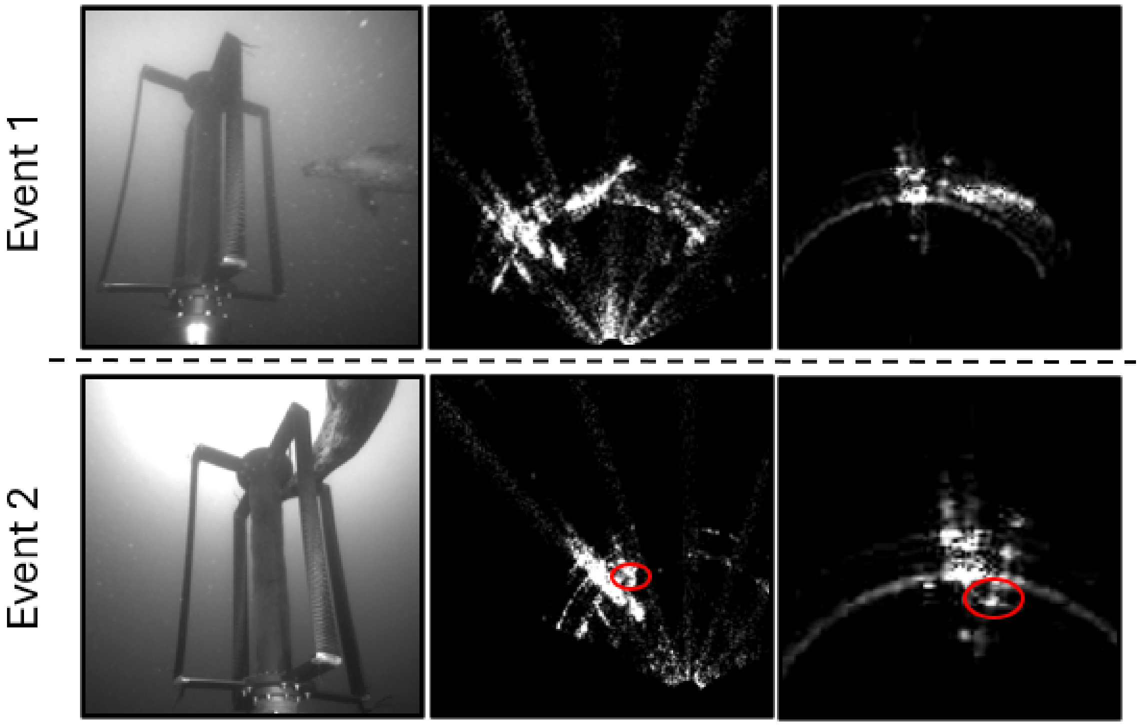

Fig. 8. Two events containing seals. During event 1 (24 Dec. at 22:52) the rotor was rotating and the seal approached it and swam in the wake. The rotor was stationary during event 2 (14 Dec. 22:15) and the seal inserted its head within the swept plane of the rotor (red circle in acoustic images). Optical images provide far more information about these events than the acoustic images.

data. However, our limited review of the imaging sonar data provides some insights into the complementary roles of optical and acoustic imaging for environmental monitoring at marine energy sites.

Following extensive reviews of optical imagery and a more limited review of acoustic imagery around specific events of interest, our view of the role imaging sonars can play in observing animal behavior around turbines remains consistent with previous suggestions in the literature. Specifically, given that no individual sensor can measure everything of interest, multiple sensors and sensing modalities are required to collect all of the necessary information to inform collision risk. If near-field (i.e., within 10s of cm) observations of animals are of interest, optical sampling provides imagery that is far more effective. The resolution and ambiguity in acoustic images make events difficult to interpret at this scale. This is evidenced by the examples of birds, fish, and seals in and around the rotor (including a fish collision) that indicate an animal presence but otherwise lack the resolution required to describe the interaction. However, since most turbines are larger than the Turbine Lander, it is typically not possible to monitor the entire turbine with a single camera. This indicates that, in most cases, it would be challenging, if not impossible, to unambiguously detect and characterize all near-field interactions with a turbine.

Due to the limitations of optical sampling in most environments, imaging sonars play an important role in evaluating collision risk. For a collision to occur in the first place an animal must approach the turbine. Only acoustic sensing can achieve the large-scale sampling of the field needed to determine if animals are avoiding the region around the rotor altogether. While optical sensors can help evaluate the outcomes of collision events, collision risk might still be determined to be low if active acoustic sensing reveals that these events are rare relative to animal presence in the area. Without far-field sampling, properly contextualizing any near-field optical observations is not possible.

Since optical sampling only becomes relevant when animals approach a marine energy converter, acoustic imagery can be used to identify periods when animals are in the vicinity of the device and optical cameras should be enabled. This is particularly relevant when ambient light is limited and artificial illumination is required for optical sampling. The large number of animals detected at night in this study (a majority of seals, fish, and fish schools) highlights the value of this approach. Effective automatic detection of animals in acoustic imagery in the presence of a moving turbine is still an active area of research. For the data presented here, automatic object detection in single image frames using established machine learning algorithms (YOLOv8; [11]) was effective for detection of animals in the optical camera data. However, this approach was less effective for the acoustic imagery due to the presence of reflections from the moving turbine and the lower resolution imagery.

It is extremely difficult to differentiate small fish from drifting plant matter in the water column in sonar imagery unless changes in trajectory are observed. Thus, while the unique scattering from seals and birds produces clear signals that are likely to be relatively easy to detect even in single images, identification of

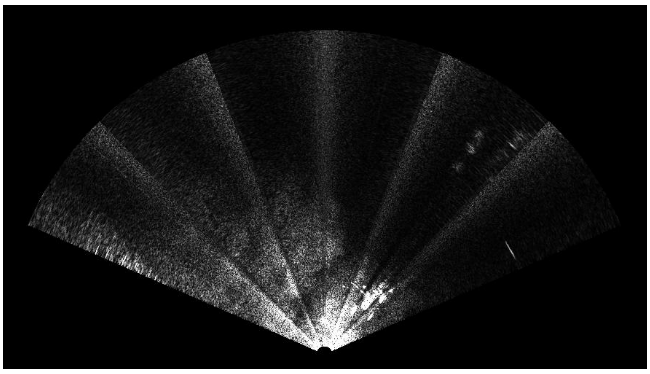

Fig. 9. An example of a Blueview image where high suspended particulate severely decreased the signal-to-noise ratio. Videos under these conditions clearly show changes in time with inflow and turbulence. Identifying animals in the imagery during these conditions is challenging.

many fish using imaging sonars is more difficult. If detecting small fishes is a monitoring objective, improved detection and tracking algorithms will be needed to facilitate active acoustic monitoring. We anticipate that this will require tracking animals across several frames to observe trajectories that deviate from objects that are passively drifting with the flow. Examples of this have been published for marine mammals [21]. In addition, the use of higher-frequency sonars (e.g. Sound Metrics ARIS, 3 MHz) may also help for detecting small, individual fish [9]. However, higher-frequencies attenuate more rapidly [22], [23], resulting in more limited ranges.

Acoustic camera data quality will also vary with environmental conditions, as was observed in Sequim Bay. Imaging sonars operate at high frequencies that are in the geometric scattering regime for all but the smallest zooplankton [24]. Fish with swimbladders scatter more sound than those lacking swimbladders [25] and the backscattering from a fish (its acoustic target strength) is often related to its length-squared [26], [27]. Based on this, one would expect larger, swimbladder-bearing fish not only to be more obvious based on their size/shape, but also due to the intensity of backscattering. For example, for a given species the backscattering from a 50 cm fish would be expected to be roughly 14 dB (about 25x) more intense than for a 10 cm fish. Thus, small fishes or those lacking swimbladders are inherently more difficult to detect using sonars.

While imaging sonars can generally achieve greater range than optical sensors, particularly at relatively low frequencies, higher frequency units that can achieve higher image resolution also face limitations in turbid waters. Scattering from suspended particulate (sediment in particulate) generally increases with f^4, where f is frequency, until the geometric scattering range is reached. While small targets may therefore have high signal-to-noise ratios at lower frequencies, high concentrations of sediment can seriously degrade image quality or mask small targets all together. Thus, to the extent possible, we recommend the use of lower frequency sonars if their range resolution and operating range are sufficient to detect the animals of interest when high suspended particulate concentrations are expected. Imaging sonars generally operate at frequencies above the hearing ranges of most animals, thus limiting any biases they may introduce [28]. Nonetheless, when using sonars with lower operational frequencies, care should be taken to ensure that potentially audible noise is not introduced. Further, optical backscattering sensors can be used to quantitatively identify periods with high levels of suspended particulate when detection capabilities might be compromised.

We found that there was not a single set of sonar settings (e.g., user-selected value of gain) that provided the highest quality data across all environmental conditions. For example, sensor settings could have been modified during the period of high backscattering from suspended particulate shown in Figure 9 to avoid image saturation and increase the signal to noise ratio. However, those settings would have resulted in a lower signal to noise ratio during conditions with less suspended sediment. Therefore, we recommend the development of adaptive processing approaches to account for natural variability in background noise levels. We note that the software provided by some instrument manufacturers (e.g., Blueview) does dynamically adjust sensor settings to optimize the appearance of objects in the field of view. However, because this is done based on objects entering the field, it results in dynamic background noise levels, which can make automatic target detection challenging. A preferable approach would be adjust sensor settings based on background conditions and incorporate information about current conditions with target detection algorithms.

Both acoustic and optical cameras can be used to study behavior to inform collision risk. However, their use and application should be informed by specific study objectives. For example, if the primary goal is to study how often animals interact directly with a turbine versus evading it, thoughtful acoustic sampling is more likely to provide the requisite information. On the other hand, if specifics regarding the outcomes of direct interactions, which could include swimming through the rotor or collisions, are needed, optical cameras may be a better approach. In either case, instrument selection should also be informed by the species of highest interest.

At larger scales (e.g., grid-scale turbines) trade-offs will be similar, though optical cameras will likely not be able to capture the entire turbine. Thus, multiple optical cameras, acoustic sampling, or a combination of the two will be required. Different acoustic sensors offer different resolutions and capabilities regarding two versus three-dimensional detection. For two-dimensional units like those discussed here, distinguishing the precise location of targets relative to moving components will be increasingly difficult, particularly at large ranges, making the classification of interactions and outcomes more difficult. In addition, targets like the small fish discussed here will be increasingly difficult to detect. However, targets like large fish, birds, and marine mammals should be identifiable where signal-to-noise ratios are not a limiting factor. As discussed above, acoustic approaches are more likely to yield evidence of interactions like avoidance or evasion than collisions and associated outcomes primarily due to limitations on resolution. Studies like Gillespie et al. [21] provide a framework for this approach, but more work is needed to understand interactions and identify any necessary mitigation strategies across a broader range of species.

V. Data Availability

Environmental monitoring data from the Turbine Lander deployment are available on MHKDR [15]. The online data includes over 600 videos from the optical camera in addition to acoustic imagery for the 70 of the events that informed this work.

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