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NOTE

Bioinspired flatfish detection using electrical impedance measurements

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Abstract

Bottom trawling for flatfish by means of tickler chains has a high ecological impact due to the continuous seabed disturbance, low selectivity and high fuel costs. This issue could be significantly mitigated by using localized startle stimuli, triggered by a detection system that selectively targets flatfishes of landable size. Flatfish, however, constitute a significant challenge for remote detection, due to their low optical and acoustical signatures. Some species of predatory fish feeding on flatfish overcome this issue by using electroreception to localize they prey, even if it is buried in bottom sediments. We take this phenomenon as an inspiration in an attempt to develop a biomimetic remote fish detection technique based on electrical impedance measurements. We constructed a detection system including a set of electrodes and a low-cost analog front-end. The electrodes were mounted on a dedicated frame and dragged above a layer of sand inside a tank with sea water and several common sole (*Solea solea*). An underwater camera was used to acquire video recordings synchronized with impedance data for reference. We demonstrate that fish presence below the electrodes manifests itself by changes in the measured resistance and reactance values. This phenomenon occurs even if the fish is covered with a layer of sand. The results demonstrate the potential of bioinspired remote flatfish detection, which could be highly useful for monitoring or targeted stimulation.

1. Introduction

1.1. Background

Many flatfish species are a common target for commercial fisheries (Rijnsdorp *et al* 2007). As demersal organisms, they are harvested using various types of bottom trawling techniques (Cashion *et al* 2018, Santos *et al* 2022)—including beam trawls with tickler chains (Boute 2022). Such means introduce constant disturbance of the seafloor and entail a significant negative environmental impact—related not only to the caused mechanical damage, but also, e.g. to increased fuel consumption of the fishing vessels and limited selectivity (Santos *et al* 2022). Electrical pulse fishing mitigates several of these issues, but it also raised concerns regarding potential injuries caused to different marine organisms (Miranda and Kidwell 2010, Soetaert *et al* 2016). Despite demonstrated advantages over tickler chain trawls, this technique has been banned in many parts of the world (Boute 2022).

The ecological impact of bottom trawling gear could be minimized if the continuous stimuli used to startle and harvest marine organisms from the seafloor would be replaced with a targeted one, triggered by an integrated remote detection system. Such a detection system would preferably target only marine organisms of interest. Flatfish detection, however, is challenging due to their stealth nature. Natural camouflage and the habit of burrowing in the sand make the optical identification with cameras extremely difficult. They also lack a swim bladder which results in low acoustic signatures and near invisibility to echosounders.

Some species of predatory fish feeding on flatfish overcome this issue by sensing weak electric signals to localize their prey, even if it is buried in bottom sediments. Such phenomenon was demonstrated e.g. in sharks and rays (Kalmijn 1971). This shows that non-propagating weak electric fields can be efficiently used to detect fish in highly conductive sea water and within seafloor layers. Some species of freshwater fish use active electrolocation to detect changes in electrical properties in the surrounding medium associated with presence of potential prey (von der Emde 1999). Active sensing by means of generating electric current flow in water and measuring induced voltage drop relies only on contrast between electrical properties of fish and ambient environment. It is independent of the amplitude of weak bioelectric signals emitted by the target, and thus can potentially ensure better detection performance than passive means. We take both of the described biological mechanisms as an inspiration in an attempt to test feasibility of electrical impedance measurements for flatfish detection.

Fundamental mechanisms and phenomena underlying electrical impedance measurements for fish detection in freshwater were described in a recent study (Nowak and Lankheet 2022). The introduced approach extended the concept of the so-called resistivity fish counters used in stock estimation in flowing waters and in aquaculture (Appleby and Tipping 1991, Smith *et al* 1996, Li *et al* 2021). Flatfish detection in a marine environment, however, presents a broad range of different challenges. First, electrical resistivity of sea water is much lower than resistivity of fresh water, approaching a short-circuit (typically approximately 0.2 Ωm for sea water vs. between 1 and 100 Ωm for fresh water (Nowroozi *et al* 1999)). As a result, the relation between the effective conductivity of fish tissues and the ambient water is reversed and detectability would depend on decreased conductance due to the presence of a fish. Second, flatfish lie on a sediment layer, i.e. at the border of two media with different electrical characteristics. They also often cover themselves with a layer of sediment. Third, as the flatfish mostly rest motionless the measurement electrodes need to move above the bottom to scan the area. Such motion might be the source of noise and disturbances of various kinds. All these factors raise questions on the feasibility of flatfish detection by means of electrical impedance measurements, and on the potential electrical signatures of fish presence. The present study addresses these questions and paves the way for further investigations aimed at specific applications.

1.2. Electrical impedance fundamentals

Electrical impedance is a quantity relating a harmonic voltage applied between a pair of electrodes to the resulting electrical current flow. It takes both amplitude and phase relations into account and is expressed as a complex number:

$$Z = \mathrm{Re}(Z) + j\,\mathrm{Im}(Z). \tag{1}$$

The real part of the impedance, Re(Z), is called resistance and it describes the voltage to current amplitude ratio for a special case if both signals would be in phase (or if signal frequency would be equal to 0). The imaginary part of the impedance, Im(Z), is called reactance and describes capacitive or inductive characteristics of the measured object. All biological samples, due to the electrical properties of cells and cell membranes are characterized with purely capacitive behavior, and their reactance is always negative (Grimnes and Martinsen 2014). Impedance is a function of signal frequency, and it depends on electrical properties of the tested sample, as well as on the overall system geometry, including shapes and arrangement of the electrodes. Properties of the measurement equipment and the connecting cables also contribute to the eventual result. The challenge for fish detection using electrical impedance is to find the signature of changes in the signal that selectively relate to absence or presence of a fish.

Although impedance measurements can be conducted with just a single pair of electrodes, it is often beneficial to use separate current carrying (CC) electrodes for exciting electric current flow within the sample and separate voltage pickup (PU) electrodes for measuring the induced voltage drop. In this case the impedance can be expressed as:

$$Z(\omega) = \frac{U_{\mathrm{PU}}\sin(\omega t)}{I_{\mathrm{CC}}\sin(\omega t + \theta)}, \tag{2}$$

where I_{CC} is the amplitude of the applied harmonic current, U_{PU} denotes the measured amplitude of the resulting, harmonic voltage, $= 2\pi f$, where f is the frequency of the applied harmonic signal, and θ is the phase shift between the current and voltage signals. Similarly, actively electrolocating fish use separate, specialized organs to generate electric current flow, and electroreceptors to sense the induced voltage drop (von der Emde 1999). In this way it is possible to mitigate the effects related to ionic double-layer formation at the electrodes' surfaces, which would introduce additional impedance components, distorting the recorded changes in impedance. This is especially important in marine environments, and we therefore use a four-electrode system.

Impedance measurements utilize low-amplitude signals and are harmless and imperceptible to fish (Nowak and Lankheet 2022). They remain harmless even in an extreme case when electrodes are pressed directly against the body of a fish (Cox and Hartman 2005, Hartman *et al* 2015).

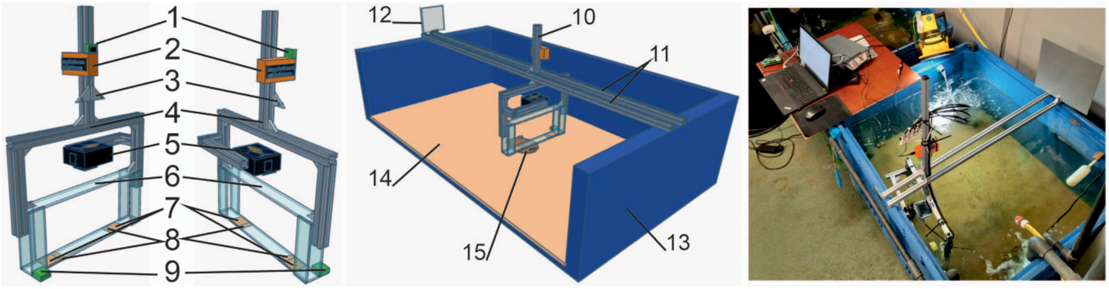

Figure 1. (a) Laboratory setup used for experimental investigations: schematic drawings of the measurement module (left), entire setup (middle), and a photograph of the actual setup (right). 1–forward-looking distance sensor; 2–distance measurement module; 3–supports/sliders; 4–aluminum frame; 5–camera; 6–transparent plexiglass frame; 7–current carrying (CC) electrodes; 8–voltage pick-up (PU) electrodes; 9–downward-looking depth sensor; 10–measurement module; 11–aluminum rails; 12–reflective screen; 13–water tank; 14–sand layer; 15–flatfish.

2. Methods

The laboratory setup used for the experimental investigations is presented in figure 1. The measurements were conducted inside a tank with dimensions 1200 mm × 1000 mm × 700 mm (length × width × height) filled with sea water (∼50 cm). A layer of sand, on average about 1 cm, was deposited on the bottom and three adult common sole (*Solea solea*) specimen were swimming freely in the tank.

On top of the tank we put a pair of guides made of aluminum v-slot profiles, arranged perpendicularly along the width. The guides were used to slide a measurement module (figure 1, left) comprising sensors and measurement equipment at a constant height above the bottom. At the end of one of the profiles we attached a flat screen made of an acrylic plastic plate, which served as a reflector and a reference for a time-of-flight (ToF) distance sensor.

At the bottom of the measurement module were four electrodes made of 0, 1 mm thick phosphor bronze plates: two outer CC electrodes with dimensions 20 × 20 mm, and two inner PU electrodes with dimensions 10 × 20 mm. The distance between the adjacent CC and PU electrodes was 2 mm, and between the inner PU electrodes—200 mm. The electrodes were attached to a transparent beam made of plexiglass and connected via shielded coaxial cables to the impedance measurement electronic circuit.

The impedance measurements were conducted using an AD5940 analog front-end (AFE) controlled by an ADICUP3029 microcontroller (both Analog Devices, USA). In-house embedded software for the microcontroller ensured streaming impedance values via a serial port at a rate of approximately 10 Hz. The measurement circuit was connected to a PC computer with a USB cable. The frequency of harmonic current/voltage signals used for measurements was set to 50 kHz, and the output voltage amplitude was limited to 800 mV peak-to-peak.

Video recordings of the measurement area were obtained with an underwater GoPro (Hero 10, GoPro, USA) camera inside a waterproof case with a sealed USB connection. The camera was mounted above the dielectric, transparent plexiglass frame, looking downward to the electrodes and 'seabed'. The camera was synchronized to the impedance measurements via the USB connection by means of an in-house Python script.

The position of the measurement module was determined using a distance measurement device constructed using a Raspberry Pi Pico board (Raspberry Pi Ltd, UK) and two ToF distance sensors (VL53l1X, STMicroelectronics, Switzerland). One of the sensors was mounted on the top part of the measurement module, above the water surface and was looking forward, measuring distance to the screen at the end of the tank. The second sensor was sealed and attached close to, and at the same height as one of the electrodes, at the bottom part of the module. It was looking downwards, measuring the distance from the bottom.

Data acquisition and processing on the host computer were conducted using in-house Python scripts, ensuring synchronization between impedance measurements, video recordings and distance measurements. During measurements the electrodes were located approximately 70 mm above the bottom. We moved the measurement module across the tank, over the positions of flatfish, which mainly remained still on the sand. In some cases we recorded the signal with stationary electrodes and one of the fish swimming below them.

3. Results

Figure 2 presents resistance and reactance values determined while moving the measurement module

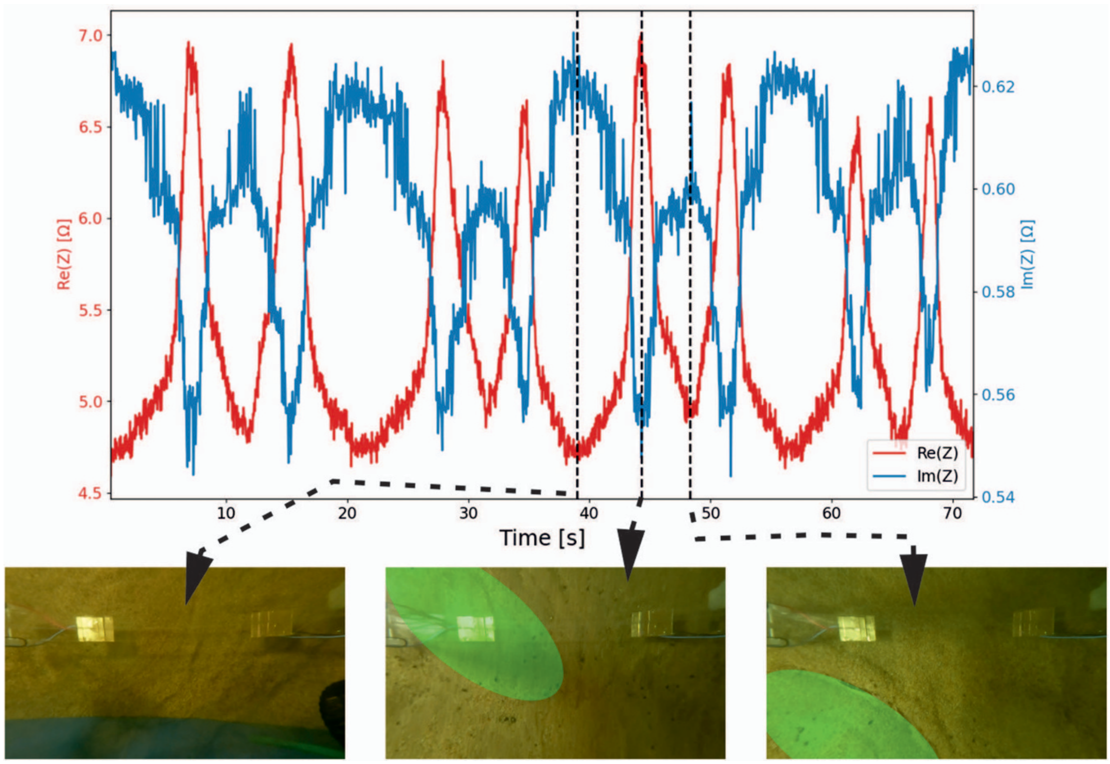

Figure 2. Resistance and reactance values as functions of time, determined while sweeping electrodes approximately 70 mm above the bottom (top plot). Images below present video frames captured by the camera at the time moments indicated by the vertical dashed lines. Green ellipses indicate approximate locations of the flatfish covered with a layer of sand.

back and forth across the tank, passing over a single flatfish buried in the sand. Fish passes are clearly visible as significant positive resistance peaks and negative reactance peaks. Extracted video frames illustrate an example of such an event, as well as an empty part in between, with only sand. Fish positions are indicated in the figure with color markings. The fish was approximately 35 cm in length.

The same results, plotted as functions of distance measured along the tank, are presented in figure 3, further systematizing the results depicted in figure 2. Lines show averages and corresponding standard deviations over eight subsequent passes. The approximate location of the fish is indicated with a corresponding icon below the plot. Flatfish presence is indicated by highly reliable increments of resistance and decrements of reactance. Highly similar results were obtained for other fish at different locations, either on top of or in the sediment.

Figure 4 illustrates results of impedance measurements with electrodes resting still close to the middle of the tank with a fish passing below. The appearance of fish is indicated by a strong positive peak if the resistance plot and a strong negative peak in the reactance plot. The time locations of the peaks correspond to the fish position just below the electrodes, as captured in the synchronized video frames. Video footage with resistance and reactance values in overlay are included in the supplementary data. The datasets used to generate the presented figures are openly available in a repository (Nowak 2023).

4. Discussion

The resistance and reactance values measured inside the sea water tank remain at steady levels when electrodes are held still above the bottom or when they are moved across the tank and no fish is present. Steady state fluctuations of the measured values are below 100 mΩ for resistance and less than approximately 40 mΩ for reactance, which includes the influence of all the noise sources. Those include both internal noise of the measurement board and external interferences originating from e.g. water pumps, electronic systems, and their power supplies. Also, in the case of the moving electrodes vibrations of the setup and movement of the connecting wires could contribute to the overall noise level—however, in the conducted experiments this influence was not significant. On this background, the changes in the measured impedance components corresponding to the appearance of a fish below the electrodes are at least an order of magnitude higher. In this regard, electrical impedance measurements proved to be valid and feasible for flatfish detection in the simulated marine environment.

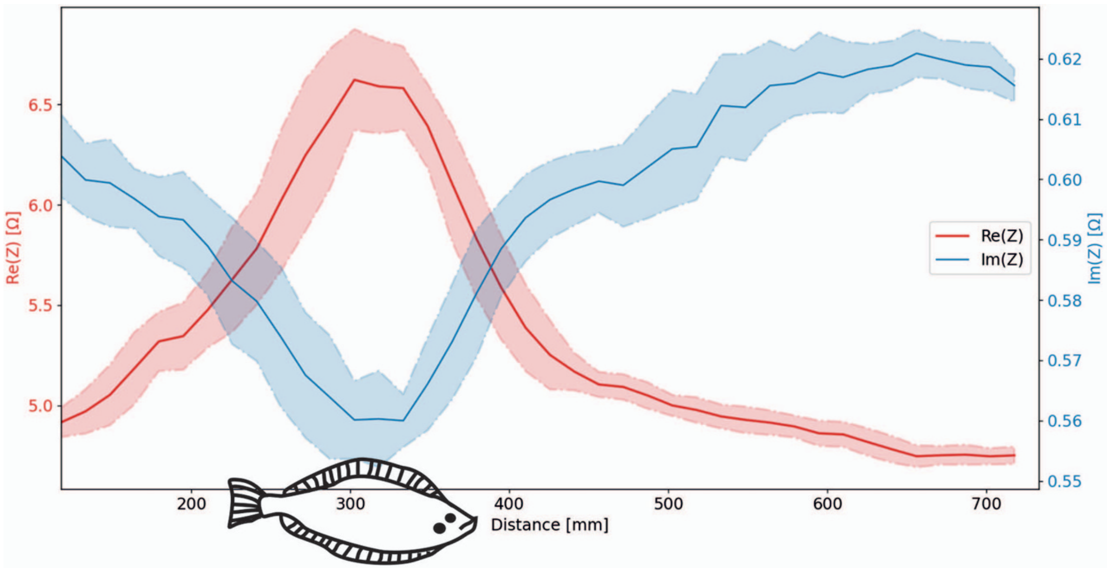

Figure 3. Resistance and reactance values as functions of distance along the tank, determined while sweeping electrodes four times back and forth approximately 70 mm above the bottom. Solid lines indicate mean values, while shaded areas indicate standard deviations. The flatfish icon indicates the approximated location of the fish on the bottom.

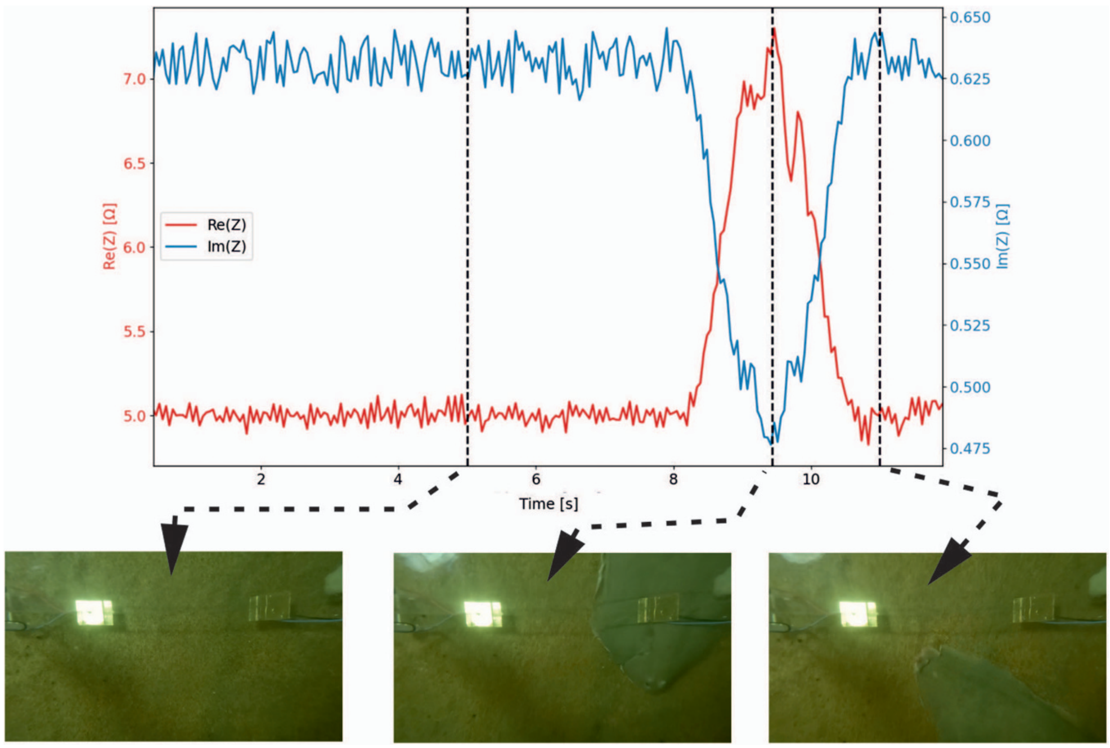

Figure 4. Resistance and reactance values as functions of time, determined with electrodes held still approximately 70 mm above the bottom (top plot). Images below present video frames captured by the camera at the time moments indicated by the vertical dashed lines. During the measurement the flatfish swam below the electrodes (visible in the frames in the middle and in the right).

The described results were obtained using electrodes dragged approximately 70 mm above the bottom. Such a close-range detection setup should be suitable for bottom fishing, in which sensors integrated with the fishing gear are dragged just above or directly on the seafloor (Boute 2022). The exact relation between the achievable detection performance and distance from a fish is complex, depending on electrode geometry and configuration, fish size and orientation, and properties of the ambient medium. It can be assumed, as a rule of thumb, that the effective detection distance will not exceed the electrode spacing (Nowak and Lankheet 2022). Those estimations seem to be in line with the observations on achievable detection ranges in actively electroreceptive fish (Moller 1980).

Bioinspired flatfish detection based on the changes in impedance values is possible thanks to differences in electrical properties between fish tissues and the ambient sea water and bottom sediments. Electrical conductivity of sea water is higher than the effective conductivity of flatfish, and thus the measured resistance value increases when a fish appears in the close vicinity of the electrodes. Although the sediment has a higher resistance than the water, this was also true for a fish in the sediment. As expected for animal tissues, the increase in resistance was accompanied by a clear decrease in reactance. Together, these changes constitute a clear signature for the presence of a fish, either for a stationary fish when electrodes are moved, or for a swimming fish underneath stationary electrodes.

All the results were obtained using a low-cost AFE, which constitutes an important step closer towards practical applications including a more selective, triggerable bottom fishing gear with a minimum ecological impact. Such a gear would generate stimuli only when the detection system would signal the presence of a fish. In this way, disturbance of the seafloor would be limited to the absolute minimum, for any type of startle stimulus that could be triggered based on detection. An obvious candidate for such a stimulus, given the availability of electrical electrodes in the system, would be a combination of detection and electrical pulsing. This would allow for a minimum of bottom disturbance as both detection and stimulation would operate remotely. Since pulsing would be required only at locations where a fish is detected, and the electrodes could be constructed in a way to only affect a limited area underneath, any potential side effects of pulsing would also be substantially reduced. Other possible applications could consist of continuous monitoring of fish densities, and only start periods of stimulation in areas of high fish densities. Yet another application could be to install measurement electrodes as counters of fish entering the net, which would allow to optimize stimulation techniques while towing, identify favorable fishing grounds and determine optimal tow durations.

In accordance with the operating principle, the impedance-based fish detection system will also react to other objects with electrical properties contrasting to the ambient medium. A detailed discussion on this topic, including underlying physical phenomena and discrimination methods would require separate, extensive studies and falls beyond the scope of the current study. Still, some important, general remarks on this issue can be briefly made. First, from the point of view of the considered bottom trawling applications, system sensitivity is much more important than selectivity. A significant reduction in negative environmental impact can be achieved even for relatively low selectivity rates, compared to non-triggered bottom fishing techniques. Second, impedance-based techniques can be integrated with other detection modalities, such as optical means, to increase performance beyond individual limitations of each. Finally, the approach introduced here offers innumerable possibilities for adjustments and discovering new ways for improvements. For instance, exploiting specific capacitive properties of living tissues (Grimnes and Martinsen 2014, Nowak and Lankheet 2022) might enable to differentiate living from non-living objects by analyzing the reactance component of the detection signal.

The present study demonstrates proof of principle for bioinspired flatfish detection using electrical impedance measurements. Obviously, the topic is rather broad and further studies and optimizations may be required for a specific type of application. Topics for further study may include:

- Determining an optimal geometry and configuration of measurement electrodes for achieving a specified spatial detection profile.
- Performance of the detection system with a broad range of seafloor sediment types and detectability of flatfish as a function of depth in the sediment.
- Influence of other marine organisms on the operation of the detection system and methods to make it more selective (in terms of both electrode/hardware configuration, as well as signal processing techniques and discrimination algorithms).
- Methods of integrating the detection system with bottom fishing gear.
- Determining optimal frequencies, or combinations of frequencies for selective detection of flatfish.
- Further fundamental studies on mechanisms and phenomena exploited by electroreceptive fish species.

We hope to address these and other related issues in our future studies. We also hope that further investigations on capabilities, behavior, and phenomena utilized by electrolocating fish can provide important cues in this regard.

5. Summary

Electrical impedance measurements allow to remotely detect flatfish on or within a layer of sand. Presence of a fish manifests itself by significant increases in measured resistance values and decreases in reactance values. The observed changes are of at least an order of magnitude higher than the total noise levels of the system. The experiments were conducted using a low-cost measurement setup, suitable for practical, large-scale applications. The introduced detection technique could be integrated with a bottom fishing gear to provide a trigger for stimulus pulses. Such an approach would enable to increase sensitivity and selectivity of the gear, while minimizing the negative ecological impact.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.6084/m9.figshare.23611875.v1.

Acknowledgments

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Ethical statement

The study includes only remote and non-invasive detection of a freely swimming fish and the techniques used are harmless and imperceptible to the animals. The study was reported to the Animal Welfare Officer at the Wageningen University and registered with Number NAE_2023.W-019. We have received the confirmation that the study is not an animal experiment and thus does not require a permission.

Conflict of interest

The authors declare no competing interests.

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