Development of an artificial sensor for hydrodynamic detection inspired by a seal’s whisker array

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Abstract
Nature has shaped effective biological sensory systems to receive complex stimuli generated by organisms moving through water. Similar abilities have not yet been fully developed in artificial systems for underwater detection and monitoring, but such technology would enable valuable applications for military, commercial, and scientific use. We set out to design a fluid motion sensor array inspired by the searching performance of seals, which use their whiskers to find and follow underwater wakes. This sensor prototype, called the Wake Information Detection and Tracking System (WIDTS), features multiple whisker-like elements that respond to hydrodynamic disturbances encountered while moving through water. To develop and test this system, we trained a captive harbor seal (Phoca vitulina) to wear a blindfold while tracking a remote-controlled, propeller-driven submarine. After mastering the tracking task, the seal learned to carry the WIDTS adjacent to its own vibrissal array during active pursuit of the target. Data from the WIDTS sensors describe changes in the deflection angles of the whisker elements as they pass through the hydrodynamic trail left by the submarine. Video performance data show that these detections coincide temporally with WIDTS–wake intersections. Deployment of the sensors on an actively searching seal allowed for the direct comparison of our instrument to the ability of the biological sensory system in a proof-of-concept demonstration. The creation of the WIDTS provides a foundation for instrument development in the field of biomimetic fluid sensor technology.

1. Introduction
The development of movement detection systems in fluid environments poses technical challenges to commercial, military, and scientific fields. While significant advances in underwater navigation, surveillance, and object tracking have been achieved in the last century with the aid of projected stimuli such as sonars, these active sensing systems often reveal the presence and location of the emitter. The development of innovative passive systems for underwater sensing should allow for expanded characterization of the surrounding environment with increased stealth. Such passive sensors have the potential to augment or possibly replace existing active sensing systems, while introducing fewer environmental cues and disturbances. In the last century, biomimetic approaches significantly improved the performance of active sonar systems for underwater object detection and characterization [1]. This was accomplished in part through refined experimental studies of echolocating dolphins (see e.g., [2–4]). Similar efforts are presently underway to develop artificial fluid-motion sensors from biological models [5–12]. Because marine animals possess the best known performance systems for the detection of submerged wakes, this project turned to
biomimicry to guide the development of an underwater sensing system based on the sense of touch.

The marine environment impedes visual perception because of light absorption and scattering as well as suspended particulate matter [13]. This constraint has contributed to the evolution of specialized mechanoreceptive systems in some animals. A number of aquatic species have demonstrated an ability to monitor their surroundings by detecting hydrodynamic signals independently of acoustic, visual, or chemical cues [14]. In particular, pinnipeds (seals, sea lions, and walruses) are marine mammals that lack specialized biosonar [15], but possess the ability to detect waterborne disturbances with their facial vibrissae (sinus hairs or whiskers) [16–19]. Within this group, true seals (family Phocidae) are particularly informative biological models for fluid sensing. Some seals hunt swimming prey in dark or murky waters and forage frequently at night when visual cues are of limited use (e.g., [20]). Additionally, blind seals have been observed to survive in the wild [21] indicating a significant role for non-visual sensory modalities. The observation that different seal species possess notable derived features in their vibrissae [22, 23] indicates a high degree of adaptive specialization—and heavy reliance on mechanoreceptive cues—within this taxon.

The harbor seal (Phoca vitulina) is the best-studied seal with respect to fluid motion sensing. Dehnhardt and colleagues [24] first tested the ability of a highly trained harbor seal to detect and report minute water disturbances in the absence of other (non-tactile) sensory cues. This study revealed detection thresholds for fluid velocities as low as 245 μm s⁻¹ in the 10–100 Hz range. Subsequent experiments highlighted refined hydrodynamic tracking performance in harbor seals by demonstrating their ability to locate and follow trails generated by a remote-controlled miniature submarine [25] as well as trails generated by other seals [18]. Trained harbor seals have also been shown to reliably determine the direction of movement of much smaller objects, including synthetic fish fins [26], and to discern the size and shape of wake-generating stimuli using only their whiskers to contact the wake left behind by a moving object [27].

The harbor seal’s ability to locate and precisely follow hydrodynamic signals holds significant promise for the development of wake detection and tracking sensors. This biological system can inspire new fluid sensing applications for use in the underwater environment. Here, we describe a sensor based on the mechanoreceptive abilities of seals that is the first of its kind to be deployed during the active pursuit of a submerged, moving target. This interdisciplinary effort required the collaboration of animal trainers, biologists, engineers, and computer scientists to support the sensor’s creation, development, and deployment. The final proof-of-concept demonstration was conducted with the instrument carried by a live seal trained to perform a dynamic wake detection and following task, to determine if the instrument could detect hydrodynamic disturbances used to guide the seal’s movements. In this paper, we first explore the initial design concept, iterative revisions, the final construction, and testing environments for the system. We finish with the performance characteristics of the instrument and an evaluation of the study’s limitations and future implications.

2. Design concept for the Wake Information Detection and Tracking System (WIDTS)

The conceptual design of the Wake Information Detection and Tracking System (WIDTS) incorporated certain aspects of the mechanoreceptive structures of harbor seals into a self-contained unit with multiple sensors that could be carried on a moving platform. The performance goal of the instrument was to detect relevant features present in underwater wakes, such as those that influence the orientation behavior of harbor seals. This goal was initially considered during previous laboratory work [28, 29] which developed and tested prototypes of individual sensors. The current WIDTS prototype was built after multiple iterative revisions of these artificial whisker sensors.

Harbor seals possess approximately 88 whiskers [30, 31] arranged in a complex array about the muzzle [31]. Seals have motor control over the array and hold the whiskers into a protracted position during hydrodynamic tracking, with the hair shafts nearly perpendicular to the axis of the body [32, 33]. This increases the size of the sensor array, as illustrated by figure 1. Although the functional significance of the array architecture is not currently understood, we presume that the spatial layout of the whiskers enables each individual sensor to receive a signal with minimal noise interference from adjacent whiskers and to collectively cover the full area surrounding the animal’s face. Following this logic, the WIDTS (described in section 4) presents an array of eight sensors with simple whisker-like extensions; the sensors are organized in a tiered, radial pattern to offset each artificial whisker from the potential flow interference of upstream whiskers, while filling the space surrounding the central WIDTS body.

The whiskers of seals are composed of an external keratinous hair shaft that is tapered along its length and compressed on the dorsoventral axis, yielding an ellipsoidal cross section [32, 34, 35]. Most seal species—including harbor seals—exhibit notable beading along the whisker length in a sinusoidal pattern [19]. The hair shaft itself extends from a hard capsule beneath the skin, where the neural elements are concentrated [23, 35, 36]. When an individual whisker is exposed to water flow from swimming motions and
interaction with hydrodynamic signals, the displacements of the hair shaft are transmitted to the highly innervated follicle–sinus complex in the capsule [19]. Seal whiskers are innervated and excited individually at the follicle, and the resulting neural stimulation likely maps to well-organized areas of the primary somatosensory cortex, as has been described for sea lions [37]. The encapsulated structure of the seals’ follicle–sinus complex informed the design of the individual WIDTS whiskers (described in section 2). The sensing mechanism is local to each artificial whisker, the depth of the sensor’s capsule is similar to that of the seals’ follicle–sinus complex, and the sensor is embedded within the WIDTS body. As in the animal, the whisker motion received at each sensor is converted to electrical signals that are routed to a central processor for recording and integration.

The first step to creating this sensory array was to develop a functional individual sensor, and prior work made progress along these lines. Barbier et al [38] demonstrated the feasibility of a successful parallel-plate capacitance-based sensor to measure deflections of an artificial whisker. This sensor transcribed hydrodynamic information, through mechanical movement of the whisker column, into electronic signals by means of capacitance change at the base of the whisker. Stocking et al [28] progressed Barbier et al’s [38] design by creating a cone-in-cone base for the sensor’s capacitance meter. Finally, Eberhardt [29] utilized the cone-in-cone design to create further revisions of a single sensor that is the foundation for the individual sensor design used in this study.

3. Individual sensor design

The individual whisker sensors in the WIDTS were designed to measure both the direction and speed of fluid movement in a saline, aquatic environment. To accomplish this, we used the same artificial whisker elements from previous efforts in our laboratory [38, 39] and significantly improved the sensory mechanism. The geometry of these whisker elements was relatively simple. In harbor seals, the length of whiskers varies from ~4 to 10 cm and the corresponding length-to-diameter (L/d) ratios range from 20 to 100; based in part on these measurements, Stocking et al [28] chose a cylindrical shape for the artificial whisker with an initial length of 4 cm and a circular diameter of 2 mm, yielding an L/d ratio of 20. The whisker elements did not reproduce more sophisticated features of seal vibrissae, including tapering of the shaft toward the tip, an elliptical or compressed cross section, or a beaded rather than smooth profile.

We explored multiple iterations of whisker design with
a capacitive mechanism for converting motion of the whisker into electrical signals that discriminate both the direction and magnitude of the whisker deflection. Initial prototypes with a flat base [38] showed a high sensitivity to movement but were delicate and sensitive to false measurements from pressure on the base. There was a clear need for a more robust design of the whisker base that improved the received signal quality. This was the primary focus of the current design effort.

After evaluating several concepts for the whisker, we settled on a cone-in-cone base design with conductive material creating parallel-plate capacitors between the facing surfaces. These plates are only approximately parallel to each other, as the nature of the cone-in-cone design prohibits a completely parallel arrangement of the plates. This design structure increases the surface area of the capacitor plates to increase signal magnitude. Figure 2 shows the cone-in-cone structure. The cones converge at their tips to create a fulcrum of rotation for the cantilever, allowing it to pivot. The inner cone is secured to the outer cone with silicone enabling fluid to completely fill and flow (surge) throughout the area between capacitor plates when the inner cone moves about the pivot point. Forces exerted on the whisker change the distances between the pairs of capacitor plates.

The system is excited by a sinusoidal signal, which allows for whisker motion to be measured as the output voltage across an electrical load impedance. The conductive plates on the outer cone are divided into four quadrants to provide directional information. The base of each whisker is covered by a thin membrane providing damping and restoring forces on the whisker, while the four quadrants of the parallel-plate capacitor (right) generate directional information.

To performance and stability. In these designs, the conductive silver epoxy covering the capacitive plates was coated with a thin waterproofing layer. This waterproofing layer introduced a parasitic capacitance in series with the conductive plates that degraded the signal strength, and the waterproofing layer also degraded over time to allow for corrosion of the underlying metal surface that further degraded the signal. While the structure of the sensor in the previous designs was effective there was an apparent need to prevent corrosion and to improve signal strength in the whisker sensor.

In the present effort, we developed a fourth revision of the whisker sensor (that makes several key improvements to previous work [28]) which was used in the tested WIDTS. Most importantly, the silver epoxy capacitor plates are gold-plated to prevent corrosion and allow for the removal of the separate waterproofing layer that previously covered the plates. This reduces the parasitic capacitance in series with the gap between the plates and substantially improves the signal strength. Further improvements include adding shielded wiring to reduce electromagnetic noise in the wires. Significantly, the depth of the inner cone (18 mm) places the fulcrum of the artificial whisker at the same mean depth of a harbor seal vibrissa (18 mm) [31]. Figure 3 shows the final revision sensor prior to the application of the PDMS membrane and being inserted into the inner cone (left) and after being integrated into the WIDTS ring (see section 4) with the PDMS membrane (right).

Measurements of the current whisker sensor showed substantially improved longevity and resolution over the version from Eberhardt [39]. Extended testing in water over several months showed no decrement in signal quality or range, showing that the gold plating effectively removed the previous corrosion issues. The gain range for the sensor was measured at 100 Hz for loads ranging from 2 Ω to 100 kΩ with distilled water in the gap. The gain range of the whisker was increased by 50% over previously tested high-

![Diagram of the basic cone-in-cone sensor design from Stocking et al. Reprinted with permission from [28] Copyright 2016 IEEE. The PDMS membrane (left) provides damping and restoring forces on the whisker, while the four quadrants of the parallel-plate capacitor (right) generate directional information.](image-url)
frequency excitation signals (over 1 MHz). This improved gain range provided the sensor greater resolution. The measured sensor output matched the theoretical values within 0.5% across this full range of loads. In addition, the changes to the sensor allowed for peak signal quality at much lower input frequencies (in the range of 100 Hz). This provided significant power savings and lower sampling rates to capture the whisker motion.

4. Individual sensor testing in a water flume

We tested the ability of the single sensor to detect the frequency content generated by a hydrodynamic wake and to detect wake crossings. The sensor performed well when detecting controlled wakes generated by upstream objects in a water flume. For these measurements, we used a calibrated Rolling Hills Research Company Model 1520 water flume (test section 152 cm long, 28 cm wide, and 48 cm deep) with velocity uniformity outside the wall boundary layer of ±2%. Cylinders with diameters of 2, 6, and 8.9 cm were mounted to a sting positioned 19.7 and 51.2 cm directly upstream of the sensor. Laminar flow speeds ranged from 15 cm s\(^{-1}\) to 61 cm s\(^{-1}\). Estimating the von Karman vortex shedding frequency (assuming a Strouhal number of 0.21), the cylinder wakes tested here should demonstrate frequency characteristics ranging from 0.34 to 6.03 Hz. The sensor response was measured on two orthogonal quadrants (associated with stream-wise and cross-stream motion) with a Tektronix 2014C oscilloscope.

The cross-stream quadrant consistently captured the frequency content from the wake. Example cases are shown in figure 4. When the 2 cm cylinder was placed upstream in a 61 cm s\(^{-1}\) flow, the sensor detected a distinct peak frequency (identified by FFT analysis) at 6.8 Hz. This closely matches the predicted shedding frequency of 6 Hz for the cylinder under these conditions. Similarly, for the case of an 8.9 cm cylinder, placed upstream from the whisker in a 15 cm s\(^{-1}\) flow, the sensor’s response showed a peak at 1.36 Hz, which closely matches the predicted shedding frequency of 1.1 Hz. Across 12 test conditions, composed of the cylinder diameter, distance to the sensor, and flume speed, the sensor measured a peak frequency within 0.1 to 0.8 Hz of the predicted frequency for that scenario. These tests demonstrated that the whisker-like sensor could reliably detect predicted shedding frequencies from a wake-generating object.

Once the sensor was demonstrated to detect the presence and frequency content of a hydrodynamic disturbance, the next step was to simulate a wake detection task. Here, the sensor remained in the middle of the water column attached to the sting, while a cylinder was swept across the width of the tank upstream from the sensor. The strongest signals occurred across the quadrant under compression owing to the inverse relationship to capacitance and distance, and the strongest response was always elicited in the stream-wise voltage. There was a clear increase in the stream-wise voltage associated with the detection of the 6 and 8.9 cm cylinders. While the wake from the 2 cm cylinder was more difficult to detect, the sensor was still capable of resolving
interception of the wake from 50 cm away in 30.5 cm s$^{-1}$ flow (i.e., from a distance of 25 cylinder widths). When the cylinder passed in front of the sensor, a change in the cross-stream voltage occurred with an increase in stream-wise voltage. These observations demonstrated that the sensors were capable of detecting an object crossing their path via sensor rod deflection from the obstruction’s wake. These trials showed that the sensor would be able to perform in the planned proof-of-concept demonstration, in which wake features could be detected in a realistic tracking task.

5. WIDTS construction and deployment

The WIDTS device enables the detection of hydrodynamic features with multiple whisker sensors in a context and configuration similar to those encountered by a swimming seal’s whisker array. The design features a slightly buoyant, torpedo-like body with eight individual artificial whiskers and their associated cone-in-cone sensors.

Figure 5 shows an exploded view of the complete WIDTS sensor array. The WIDTS body has a conical head and octagonal form factor down the length of the body to provide eight flat surfaces, one for each cone-in-cone sensor. The eight whisker-like sensors are distributed radially around the body and embedded in two octagonal rings. The rings are hollow, and a shallow cavity near the inner edge of the side of the ring allows for O-rings between each component of the WIDTS to maintain a waterproof interior. The octagonal rings carry four whiskers each, and each individual whisker occupies one face of an octagonal ring.
also figure 3). The two rings are offset by 45 degrees so the whiskers do not overlap in the front view and the wires connected to the capacitive plates on the outer and inner cones of each whisker run to the inside of the ring via a waterproofed hole. A bite plate attached to the back of the instrument enabled a trained seal to carry the device clenched firmly in its mouth and directly in front of its own whisker array.

A 5 cm × 13 cm custom printed circuit board (PCB) inside the middle of the WIDTS body is held in place by a slot on the inside of the ring sections of the WIDTS. The PCB’s custom-designed electronics excite all eight sensors with a sine voltage waveform, acquire returning output signals, sample the peak voltage values from each whisker quadrant, and store the output data to memory. The PCB, which is powered by a 3.6 V lithium-ion battery, excites all whiskers with a 790 Hz sine wave, terminates the received signal with an on-board resistor, and extracts the gain range with a peak detector. The signal is sampled and digitized at a rate of 512 Hz and stored to memory.

The selected sampling rate was constrained by the microcontroller and the absolute sampling rate of the electronics. The selected sampling rate was constrained by the number of ADC inputs. Data were later verified by comparing sensor output with the overhead video tracks of the swimming seal. This mitigated some of the issues associated with undersampling; however, the low sampling rate remains a limitation of the electronics. The data collected by the WIDTS can be transmitted wirelessly over Bluetooth radio to an external base station (laptop) via a custom Java computer program. Importantly, the board also includes three gyroscopes and three accelerometers to correlate the orientation of the board and head movement artifacts to measured data acquired at the whisker sensors, since head motion might cause the whiskers to experience motion caused by drag through the water.

It was necessary to deploy the WIDTS adjacent to the seal’s own vibrissae to enable field testing of the WIDTS in a realistic environment used by the biological sensory system. The bite plate allowed the trained seal to hold the WIDTS directly in front of its own whisker array, exposed to the same hydrodynamic information the seal would receive when tracking a moving target. However, the size and placement of the WIDTS raised concerns that it would obstruct the seal’s sensory abilities and thus tracking performance. To examine the impact of the WIDTS body on the flow field received by the animal, we created a 3D-printed model of a juvenile harbor seal head from available CT scan images (the model head was smaller than that of the adult test subject, representing a ‘worst-case’ disturbance scenario) and evaluated the flow dynamics surrounding both the WIDTS and the seal’s head.

Particle image velocimetry (PIV) measurements of the flow field around models of the WIDTS and the seal head were obtained in the water flume described in section 2. These were used to verify flow field modeling in ANSYS CFX. Summary results of the modeling are shown in figure 6 (for details see [29]). The ANSYS CFX flow-field simulations revealed an area of low-speed recirculation between the WIDTS and the seal nose. Fluid flow directly downstream of the WIDTS edge was slowed near the seal’s muzzle until encountering the contours of the seal’s head. Flow velocities were compared at points near to (<1 cm) and far from (>1 cm) the seal’s nose. The far point (located in the field of the seal’s whisker array, figure 6) did not experience changes with the introduction of the WIDTS. Because the vibrissae act as cantilever beams with an end fixed at the seal, the forces acting further out along the whisker have a greater influence on the whisker’s deflection. As a result, the far field velocity magnitude is likely to play a larger role in the information gathered by the seal than that of the near location point. With this in mind, we predicted that the instrument would not substantially block the hydrodynamic information received by the seal. We did not explicitly model the potential disturbance created by the artificial whiskers on the seal’s own whisker array.

After the design and modeling phase of the WIDTS was complete, we 3D-printed the WIDTS nose cone and cast the ring sections in epoxy. Four whisker sensors were hand-assembled in each ring section with their outer cones covered by PDMS and with distilled water in the gap between the cones. Due to this design, occasional refilling with distilled water was required; future iterations of the sensors would aim to reduce evaporative water loss. The base plate and bite plate of the WIDTS were cut from plastic, and the bite plate was covered in neoprene for the seal’s comfort and extra grip. The entire assembly was secured by bolts that ran from the base plate through the ring sections to a nut in the nose cone (figure 2).

6. Biological performance of a trained seal; test subject and environment

To enable a proof-of-concept demonstration of the WIDTS, we worked closely with a captive seal that could track moving objects under water using only hydrodynamic trails. The subject for this study was a male Pacific harbor seal (P. vitulina) named Sprouts (identification NOA0006602). The seal was 22 years old at the start of the study and had extensive prior experience in performing trained behaviors for research purposes. This individual was housed in an outdoor, circular seawater-filled pool (1.8 m depth and 7.6 m diameter) with adjacent haul-out decking at Long Marine Laboratory in Santa Cruz, CA. All husbandry and research-related tasks relied on standard operant training methods, using positive reinforcement. Training for this task occurred between 2010 and 2013, during which time the seal participated in wake-following sessions between two and five times
per week. The seal received about one-third of his daily diet as reward for cooperative behavior during these training sessions, which typically included 10 to 20 trials. No aspects of the research were invasive or involved restraint or food deprivation.

The research activities were conducted with the approval and oversight of the Institutional Animal Care and Use Committee at the University of California at Santa Cruz, with federal authorization from the National Marine Fisheries Service of the United States (marine mammal research permit 14535).

The seal was gradually trained to find and follow wakes while simultaneously wearing a blindfold and carrying the WIDTS instrument firmly in his mouth. The seal was initially taught to swim and eat comfortably while wearing a blindfold made of visually opaque neoprene. He also learned to detect and follow a turbulent underwater wake created by one of two different moving objects in his pool. The wake-generating object used during the initial stages of training was a simple sphere (racquetball, 7 cm diameter) dragged through the water by a 2 cm-diameter rigid steel pole. Later, we introduced a self-propelled, remote-controlled submersible with physical characteristics suitable for the eventual WIDTS field tests. The submersible was a Thunder Tiger Neptune SB-1 submarine (length 78 cm, height 21 cm, beam 18 cm, propeller size 5 cm, 12 V motor propulsion) which operated at a speed of 0.5 m s$^{-1}$ and a maximum depth of 1 m. The top speed of the submarine was less than the normal swimming speed of harbor seals, but the seal was trained to slow his swim to match the speed of the submarine. The time delay between the start of wake generation and the release cue for the tracking behavior was progressively increased, from very brief delays (0.5 to 2 s) to delays as long as 15 s. Although the seal could have performed the task with much longer delays, we used a maximum 15 s delay to avoid overlap in hydrodynamic paths in the pool at the start of each trial. In all cases, the seal was rewarded for following the path of the wake-generating object at a fixed distance of ~0.3 m, with continuous tracking durations ranging from a few seconds to more than a minute. The final component of training was for the seal to carry a mock WIDTS instrument in his mouth while performing the task.

The seal was trained at first to carry only the bite plate while performing the wake-following task, and then the bite plate was fitted with a mock-up of the WIDTS (i.e., without electronics). We found that following practice with the instrument, the seal’s wake-following ability was not notably impeded by the body
of the WIDTS. Further, despite holding the bite plate firmly between his teeth, the protraction of his whisker array was not different with and without the WIDTS. By the conclusion of training, the seal had learned to readily perform the wake-following task while wearing the blindfold and carrying the mock WIDTS securely in front of his own whiskers (supplementary video 1). He had also learned to carefully return the WIDTS to his trainer at the end of each trial before receiving a fish reward.

During experimental trials the blindfolded seal carried the WIDTS while finding and following the trail generated by the self-propelled submarine. The submarine was controlled remotely to follow predetermined paths ranging from simple circuits around the edge of the pool to more complex variations involving one or more direction changes. Sessions were varied, alternating between test trials with the seal carrying the WIDTS and behavioral maintenance trials that involved the seal carrying the mock instrument or no instrument. The experimental trials lasted from 15 to 75 s, and the maintenance trials lasted from 1 to 75 s. All trials were recorded by a wide-angle video camera suspended directly above the center of the pool to enable time-synched performance evaluation of both the seal and the instrument.

The blindfolded seal was able to find and then follow the generated wake on all experimental trials. That is, the seal would find the path of the wake-generating object, and then maintain a consistent following behavior that reflected the movement patterns of the object. Despite a delay of up to 15 s between the onset of the submarine’s movement and the release of the seal by the trainer, the seal could accurately detect the wake as soon as he crossed its path. Additionally, he could resolve the direction of the moving object from the available hydrodynamic cues, altering his course immediately upon intersecting the wake. Further, he could follow the wake vertically as the submarine’s path was varied between the water’s surface and the maximum depth tested (1 m). We often observed the seal sweeping his head from side to side while performing the task, which is consistent with descriptions of find and follow behavior in seals [18, 25]. This behavior was most evident when the seal was released to locate a hydrodynamic trail, but also occurred when the seal was following a stimulus that was turning or dipping in an unpredictable pattern. In contrast, the seal rarely moved his head in an up–down motion. There was no notable difference in head-weaving in trials where the seal carried or did not carry the WIDTS.

While we did not use a deliberate acoustic masker to cover potential sound localization cues provided by the moving objects, we are confident that the seal used hydrodynamic cues to find and follow the hydrodynamic trails. During testing and training, there was steady water flow into the tank that generated broadband noise that would have diminished available acoustic cues. More importantly, it was obvious that the blindfolded seal never used dead reckoning to find the wake-generating stimulus; rather than taking the acoustic path (the shortest path), the seal would search slowly in a general area until he detected the hydrodynamic trail, and then turn quickly and immediately in the correct direction to follow the path (supplementary video 1).

7. Field testing and analysis of WIDTS performance

Our objective for the field test was to determine whether the ability of the WIDTS sensors to detect submerged wakes in the lab would translate to a dynamic testing environment, similar to that used by the biological model. We hoped to show that some of the features of the hydrodynamic path that guided the seal’s tracking behavior were also detectable by the WIDTS. Our approach for this proof-of-concept demonstration was to observe how WIDTS detections related to changes in the harbor seal’s wake-tracking behavior. By coupling the WIDTS to the harbor seal via the bite plate held securely in his mouth, the sensors were exposed to a hydrodynamic environment similar to that encountered by the free-swimming seal. This is illustrated by figure 7, which shows the blindfolded seal following the path of a dragged object while carrying the complete instrument package.

Before conducting experimental trials, we evaluated the wake produced by the moving submarine in the water flume described in section 2, and then verified that the WIDTS could detect the submarine in the testing pool used by the seal.

As with the seal head modeling effort, we obtained PIV measurements in the flume to characterize the wake produced by the radio-controlled submarine. This evaluation provided useful but limited information due to the large size of the submarine relative to the size of the water flume. The diameter of the submarine blocked 37.8% of the flume cross-sectional area, which accelerated water flow and constrained the width of the wake left by the submarine’s propeller. Therefore the flume measurements provided only a minimum estimate of the width of the wake. PIV sampling (five sections of 18 by 30 cm with 500 image pairs in 15 cm increments as the submarine was moved forward in successive steps) allowed the flow field 70 cm behind the sub to be captured with good resolution. The results indicated that the wake should cover an area at least as large as the submarine’s diameter and that the wake is likely to persist for several body lengths with measurable velocities (for details, see [29]). Visualization of the surface wake visible in the seal’s testing pool confirmed these minimum estimates.

To demonstrate that the WIDTS could detect the wake of the submarine in the test pool, the submarine
was held stationary and the WIDTS was manually swept behind it and through the propeller stream at a range of 0.5 m. Overhead video footage indicated when in time the WIDTS was directly behind the submarine. Figure 8 shows the measured outputs of the WIDTS’s accelerometer and of the horizontally positioned whiskers on the left and right sides of the WIDTS during one trial. As the WIDTS passed from left to right, the right sensor reported a detection just before the main WIDTS body was directly behind the submarine, and the left sensor detected flow immediately after. The opposite happened when the WIDTS swept back through the wake from right to left; the left sensor detected the wake just before the body was directly behind the submarine, followed by the right sensor. The accelerometer data show the change in
direction of the WIDTS in between passes through the wake. These data confirm that the WIDTS sensors could detect the submarine’s wake in the testing pool. Further, the data gathered by the accelerometers and gyroscopes confirmed the horizontal movement patterns in the body of the WIDTS.

Experimental pursuit trials with the seal were recorded by the wide-angle video camera mounted directly above the testing pool. A custom motion analysis program made in Matlab identified both the WIDTS and the submarine in the video footage by their color, and tracked the center of these objects as they traveled around the pool. The plotted tracks could be viewed as animations of the progressing trial, or as a composite image of the entire trial. A review of the seal’s performance data across the test trials indicated that he closely followed the path left by the submarine, whether he was carrying the WIDTS or not. Figure 9 shows a composite track of a simple trial, while supplementary video 1 shows an example of the seal finding and then following a more complex path.

On all trials, the seal was able to find and then follow the hydrodynamic path with a high degree of accuracy, typically remaining within 0.3 m of the path taken by the submarine. The WIDTS did not interfere with his performance, and although the effect of the artificial whiskers had not been modeled, and he had not practiced with artificial whiskers on the mock instrument, he had no difficulty in performing the task with the full WIDTS unit. On most trials, some weaving in and out of the wake was observed, as seen in the movement of the red tracking line in figure 9. In general, the seal appeared to have a preference to stay just on the outside boundary of the submarine’s path.

The overhead video was correlated to the data transferred from the WIDTS after each trial to examine the extent to which the artificial sensors respond to the same stimuli as the seal. Figure 10 depicts an instance where the WIDTS sensor detections correspond to the location of the submarine wake during an experimental trial. At 27.2 s into the pursuit, the seal carried the WIDTS just to the left of where the submarine had passed (the former location of the submarine indicated with a red ellipse). He crossed the wake and was on the right side of the wake at 29 s. These times are marked with red lines on the right and left sensor output data. Each line coincides with a detection spike; the right sensor detects at 27.2 s (when the WIDTS was on the left of the submarine wake) and the left sensor detects at 29 s (when the WIDTS was on the right of the submarine wake). These data are representative of the wake crossings observed during the trials. While head motion, rather than wake detection, could be a possible explanation for these detection events, movement data from the accelerometers and gyroscopes, as well as the time-synched overhead video, indicate that this was unlikely to be the case.

8. Discussion

This work accomplished two major objectives. First, it built upon a previously fabricated concept for a
biomimetic, whisker-like, individual fluid motion sensor by improving its mechanical design and developing its sensitivity to identify specific wake characteristics. We created an array of eight individual, capacitance-based, cone-in-cone cantilever sensors, each offset by 45 degrees, into a complete WIDTS that is capable of identifying hydrodynamic wakes generated by simple and complex objects. Second, this work provided a proof-of-concept demonstration that the WIDTS could detect encounters of underwater disturbances on a moving platform, which represented realistic environments for sensor application. The field testing conditions were similar to the environment encountered by the imitated biosensory system; while swimming, a trained seal carried the experimental device immediately adjacent to its own vibrissal array. Observations of the field trials give every indication that the WIDTS successfully detected the same hydrodynamic disturbances that triggered changes in the seal’s tracking behavior, providing further evidence that artificial whisker arrays can achieve underwater sensing capabilities.

To our knowledge, this is the first time such an array of hydrodynamic sensors has been used in a realistic environment to detect a freely moving source object. While field testing in the current scenario relied on data from only two of the instrument’s eight sensors as a result of time limitations and some technical issues, the design of the instrument allows for more robust, spatially integrated measurements in the future. Additional refinements can further improve the sensitivity and accuracy of this sensor system. The WIDTS will certainly benefit from developments that reduce electrical noise and increase the resolution of output data. Such improvements will enhance the ability of the instrument to detect and identify subtle wake characteristics.

The ability of an artificial sensory system to detect and report fine-scale attributes of hydrodynamic stimuli will lead to improved identification of source objects in the presence of environmental flow noise. Different object shapes, and objects traveling at varying speeds, leave different ‘footprints’ in water, and it is crucial to understand how these stimulus differences influence a wake’s signature. Such research has
recently been conducted to describe the hydrodynamic characteristics of the wakes produced by swimming fish, which in turn has provided insight into the structure and function of the seal’s tactile sensory array [40–42]. This work in the biological domain underscores the importance of accurately defining the characteristics of target wakes. Improving knowledge of wake characteristics unique to source objects will support decision-making for whatever operator or algorithm is interpreting the WIDTS output data.

An additional need is for the continued refinement of the sensor design to more thoroughly evaluate and mimic the unique morphology of seal vibrissae (see e.g., [43]). Pinnipeds possess the most highly specialized vibrissae of any animal group, and the unique morphology of these structures is thought to enable their unsurpassed ability to extract complex information from hydrodynamic flow fields [19]. For example, the elliptical cross-sectional profile of the whickers of seals and other pinnipeds (in contrast to the circular profile of those of terrestrial mammals) may play a role in noise reduction, thereby affording an advantage over a structure with a circular profile [32]. In addition, most species of seals have a repeating series of undulations or ‘beads’ along the surface of their vibrissae that do not occur in any other animal group (Ginter et al 2012, 2010). The fine-scale structure of these undulations acts to suppress vortex-induced vibrations that would otherwise be generated by the animal’s movement through the water [33]. These features of seal whiskers that apparently serve to increase signal-to-noise ratios have been shaped by evolutionary pressures; such design features could be evaluated and incorporated into the WIDTS to advance the capabilities of the artificial sensors to more closely simulate those of the biological system.

Much of what we observed through this work raises questions regarding exactly how seals (and other animals dependent on fluid-dynamic information) perceive wakes in their aquatic environment. Animal behavior can be a valuable window into nature’s advanced stimulus detection systems, and analysis of the wake-tracking behavior of harbor seals in controlled conditions can inform effective tracking algorithms and methods. For example, the seal often swept his head from side to side while finding and following submerged wakes. This movement could be interpreted as search behavior, or repeated edge detection of the hydrodynamic path, although additional research is needed to describe the pattern of head motion relative to wake diameter. These observations may be helpful in developing algorithms for adaptive wake-tracking technology. Such seal-inspired algorithms could achieve correction strategies for the WIDTS or WIDTS-like sensors such as ‘if drifting right, veer left’, and could easily work multidimensionally.

In addition to providing a proof-of-concept of the instrument design, the field tests revealed several weaknesses in the prototype WIDTS. Waterproofing the WIDTS body and sensor membrane threshold presented a constant challenge, as uneven surfaces at the O-ring interfaces caused slow leaks during testing. The uneven surfaces likely arose from the 3D printing process used for the nose cone, so it is possible that a different manufacturing approach could prevent the leakage. Flooding resulted in the loss of one PCB. While the sensors were excited at 790 Hz, aliasing resulted from undersampling the output data at 16 Hz when all thirty-two quadrants, three gyroscopes, and three accelerometers were recorded simultaneously. Sharp oscillations in the data, initially attributed to noise, were deemed a result of aliasing. Finally, a blackening of the gold-covered capacitor places was noticed during testing in seawater, which had not occurred until the PCB was used to excite the sensors. The blackening of the capacitor plate surface appears to further increase noise in the sensor output and is hypothesized to have resulted from higher currents generated by the PCB than the function generator used in individual sensor prototyping.

The quality and correlation of video data, movement data of the instrument, and detection data from the instrument could also be improved. For example, poor image quality from the video camera often reduced our software’s ability to follow the seal and the submarine in less-than-ideal lighting. The object-tracking software groups pixels using highly contrasting areas, and algorithms follow these areas from frame to frame. Often, direct sunlight brightly illuminated the pool bottom and wind textured the surface of the water; both of these conditions made it harder for our software to continuously and accurately track the trained harbor seal and the submarine. During the project, we did not attempt to merge the data stream from the video recording with the data streams from the WIDTS in a dynamic manner. A correlated interface for data evaluation would be useful for advanced data interpretation.

The submarine used during field testing was not an ideal wake generator; it was relatively large, slow, and bulky, and was limited to a radio-controlled depth range of 1 m in seawater. While we tracked the motion of the submarine from its center, the wake was produced from the rear of the object and water was typically displaced to the outside of the circular pool; the deviations of the seal from the submarine’s path in figure 9 may reflect this difference. Smaller objects with more constrained flow fields would be useful to test with the WIDTS. During training, the seal showed excellent dynamic wake-tracking behavior with much smaller objects. For example, the blindfolded seal could easily discriminate between the sphere it was trained to follow and the rigid pole that dragged the sphere though the water column (a difference of 5 cm). Identifying a smaller and faster wake-generating option that could create distinctive hydrodynamic
paths in a large area would be helpful for the biomimetic comparison.

To view this effort in a broader context, behavioral evidence has clearly demonstrated that seals use their vibrissa to determine the size, shape, and movement direction of submerged stimuli from hydrodynamic trails. Although the underlying functioning of the animal’s sensory system is not fully understood, biologists have begun to explore the mechanisms supporting its advanced capabilities and to identify aspects of incoming signal characteristics that support wake detection. Our attempt to develop an artificial sensor array that could detect hydrodynamic events relevant to the wake information received and used by seals has resolved several technical challenges and identified more. Further development of hydrodynamic sensors can continue to incorporate emerging knowledge of the seal’s sensory system, so that these artificial systems can progress beyond basic detection of hydrodynamic events towards improved characterization of wake-generating stimuli. The interdisciplinary nature of this project drew inspiration from animal behavior and research on sensory capabilities to build and test a novel hydrodynamic wake-sensing system. The design of the WIDTS and the results herein advance our ability to replicate the seal’s remarkable mechanoreceptive sensory abilities.

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Author contributions

W C E conceived the project, designed the instrument, and collected and analyzed the data. B F W assisted with data collection and wrote the manuscript. C T M assisted with data collection and manuscript preparation. C C trained the seal, and wrote the manuscript. Y S assisted with instrument testing and interpretation of data. B H C was involved in all aspects of the study and was responsible for funding. C R conceived the project, supervised animal research, and wrote the manuscript.

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