A Biomimetic Quasi-static Electric Field Physical Channel for Underwater Ocean Networks

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ABSTRACT
Nature has had millions of years to develop and optimize life in the ocean. Nocturnal oceanic animals and those that live at depth cannot rely upon optical notions of vision to navigate, hunt, or avoid predators. Instead, many rely upon an electroreceptive capability achieved through a dense grid of electric field (Voltage) sensors. In this work, we develop and characterize an artificial system which seeks to mimic this capability. The detection range of our resulting prototype was \( \approx 5 \text{ cm} \). The position accuracy in the middle of the transmit axis was \( \pm 5 \text{ cm} \) after calibration.

1. INTRODUCTION

The development and deployment of wireless underwater networks has been limited due to the lack of an accommodating physical channel. Acoustic pressure-wave systems suffer from frequency-dependent bandwidth and attenuation, time-varying multi-path, and the low speed of sound in water, while optical and conventional radio systems suffer from severe attenuation. Nature, on the other hand, has had millions of years to develop and optimize life in the ocean. Many fish species are organized into social communities and society requires effective and reliable communication to flourish. Survival itself dictates that jamming-avoidance (multiple access), self-recognition (modulation), localization, and all-weather availability (active) are requisite qualities in a physical channel so evolution has naturally selected for them.

In this work we present a novel underwater proximity sensor that mimics the ability of some Teleost and Chondrichthyes fish species [1] [12] [6] to detect and utilize quasi-static electric fields [3]. The contributions include (1) the application of theory to explain the observed performance and predict future design improvements, (2) experimental proof of the existence and utility of the phenomenon, (3) an engineering validation of the rationale for the naturally observed weak-electric fish waveforms, and (4) the design and implementation of a working short-range proximity sensor for underwater wireless network neighborhood discovery and station keeping. In the case of mobile network nodes, this sensor could assist in collision avoidance and formation management.

2. PHYSICAL CHANNELS

A physical channel may be used for sensing, communication, or actuation. In this work we focus on the development of an active sensor. Necessarily, this entails the transmission of an encoded signal and the detection of environmental disturbances to that signal. Consequently communication or actuation through the channel is also possible. Future work will explore these boundaries.

2.1 Acoustics

At a molecular-level, acoustic communication systems rely on displacing the mass of the molecules in their way. Accordingly, pressure waves can not exist without matter and propagate better (e.g. faster) as density increases, but at a higher energy per distance cost. Physical displacement requires mechanical action and is limited in frequency and amplitude by the capabilities of mechanical excitation. Long-range (large amplitude) vibration can not be achieved at frequencies in excess of the order of kHz and any vibrating sources in the environment will interfere (including reflections of the transmitted signal from the surface, bottom, and suspended objects).

2.2 Electromagnetics

In contrast, electromagnetic (radio) systems rely on aligned charge movement releasing energy. As charges move, reverse direction, and move again the conservation of energy laws require that momentum dissipate prior to the reverse in direction. This extra energy is radiated outward in the form of electromagnetic (EM) waves. EM waves propagate best in a vacuum where there are no intermediate particles to col-
lie with, which would result in absorption and scattering. Electromagnetic propagation through water is very different from propagation through air because of water’s high permittivity and electrical conductivity. Plane wave attenuation is high compared to air and increases rapidly with frequency. The principal problem is that mobile charges respond to the incident EM wave, which by absorption increases their energy level. By acting to restore their former lower energy state, the charges radiate EM waves with opposite polarity (180° out of phase). At some distance away (the far-field) the incident and re-radiated (scattered) waves appear near equal in amplitude and add destructively.

2.3 Electrostatics

Figure 1: The Ampulla of Lorenzini is a fundamental component of the electric-field sensing organ in some Teleost and Chondrichthyes fish species.

2.3.1 Electrosensory Organs in Fish

In the eighteenth century, Italian biologist Stephan Lorenzini observed a peculiar pore and organ system in crampfish [11] and theorized that they might be used for navigation and hunting. These structures were later named the Ampullae of Lorenzini in his honor. However, the purpose of the ampullae was not clearly understood, and electrophysiological experiments suggested a sensibility to temperature, mechanical pressure and possibly salinity [6]. It was not until 1960 that the ampullae were clearly identified as specialized receptor organs for sensing electric fields [1] [9] [20].

Each ampulla is a bundle of sensory cells containing multiple nerve fibers. These fibers are enclosed in a gel-filled tubule which has a direct opening to the surface through a pore. The gel is a glycoprotein based substance with the same resistivity as seawater [5]. Consequently, the ampullae can detect electric fields in the water through the Voltage differential at the skin pore versus the base of the electroreceptor cells – that is, the difference in neurological activity between the terminal axons at the pore and those in the interior vesicles of the ampulla [6] as shown in figure 2.

2.3.2 How to see like a fish!

Nocturnal oceanic animals and those that live at depth cannot rely upon optical notions of vision to navigate, hunt, or avoid predators. Instead, many rely upon an electroreceptive capability achieved through a dense grid of electric field (Voltage) sensors whose anatomy was just previously summarized\(^{1}\). However, relying exclusively upon a passive receptive capability precludes the detection of passive targets in the environment such as rocks and other navigational hazards.

The electric organ (EO), as distinct from the electrosensory organ, is present in these fish to establish a Voltage gradient in the water. This is accomplished by the direct conduction of current generated in the EO into the surrounding environment during an event known as an Electric Organ Discharge (EOD).

In order to intuit how current flows around the fish in the ocean consider: If two electrodes were placed at either end of a wide flat conductive plate and energized, the majority of the current in the plate would flow from the cathode directly to the anode along, or very close to, the direct path between the electrodes. However, as the current in any direction is composed of like polarity charges there is a repulsive force between them. This causes some of the charges to take a less direct, more circuitous, path. The current is tracing out the lines of force created by the potential difference between the electrodes as shown in figure 2.

When an object less conductive than the ocean water (rocks, plastics, bubbles, etc) is placed in the field (as is the case in figure 2), the current, following the path of least resistance, will shunt around it. This redistribution of current spreads out the field lines changing the location of the isovoltalic line’s intersection with the fish’s body – effectively casting an electrical shadow by creating a region where the Voltage is more constant per unit distance along the body. Objects more conductive than the background water have the opposite effect, concentrating the field lines, creating an electrical bright spot – a region of rapid Voltage change per unit distance along the body. Accordingly, when electroreception is an active sensor, a mimetic system can not only detect and locate objects, but classify them as well.

2.3.3 The physics of electrostatic fields

Electrostatics, as the name implies, involves the use of electric (E) fields which are, traditionally, invariant with time. For our purposes it is illustrative to consider a sequence of time-invariant fields with each successive field having more (then less, then more, etc) strength than its predecessor. When this approximation is valid, the field is said to be quasi-static [16].

In order to prove the validity of this assumption, consider that when the electric field, and hence the current flowing in

\(^{1}\)There are actually several known types of electroreceptors in two broad categories: ampullary, i.e. figure 1, and tuborous [5].
the field, changes with time two currents must be considered – the conduction current and the displacement current.

The conduction current is Ohmic [7] resulting from the movement of charges between atoms², while the displacement current results from the movement of bound charges within an atom (typically caused by the application of some external field) [18].

The most obvious example of displacement current is the vacuum-gap capacitor (two plates with nothing between them) in which the same amount of conduction current enters one plate as leaves the other. Between the plates, in the vacuum, there can be no conduction, but a magnetic field exists there as if a conduction current were flowing [15]. This phantom current is the displacement [14].

\[ j_{\text{conduction}} = \sigma E \] (1)

The conduction current is defined by equation (1) [16], where \( j_{\text{conduction}} \) is the current density, \( \sigma \) is the unit length conductivity, and \( E \) is the applied field strength. By inspection the similarity to Ohm’s law \( (I = V/R) \), where \( \sigma = 1/R \), is obvious. As conduction current is Ohmic it is stateless and time-invariant. However, the displacement current, defined by equation (2)³ [16], is based on the first time derivative of the electric field intensity and, accordingly, is not time-invariant.

\[ j_{\text{displacement}} = \epsilon \frac{\delta E}{\delta t} \] (2)

In order to qualify as quasi-static, the field must be mostly (quasi) time-invariant (static). That is, for a sinusoidal time-varying field \( E = E_0 e^{j\omega t} \):

\[ \frac{j_{\text{displacement}}}{j_{\text{conduction}}} = \frac{\epsilon}{\sigma} \omega \ll 1 \] (3)

Ocean water, with \( \epsilon/\sigma \approx 10^{-9} [19] \), is quasi-static to almost 100 MHz. This concurs with the observation that EM radiation is transmitted poorly in water, while direct conduction works extremely well.

Finally, it is important to note that despite the applicability of static analysis, quasi-static fields are time variant. The phase velocity of electromagnetic phenomenon decreases as a function of the permittivity. For seawater, with a permittivity near 80 [19], the propagation velocity is two orders of magnitude slower than in air (equation 4).

\[ v_{\phi} = \frac{c}{n_r} \] (4)

This lower velocity results in an equivalent reduction in the near-field radius and a corresponding improvement in resolution for localization algorithms applied over this channel.

3. TRANSDUCER DESIGN

Using data from a dissection of an adult male Oman shark [6], we endeavored to create an artificial Ampullae of Lorenzini organ system. To that end, we considered 1400 ampullae per shark at 8 vesicles per ampulla and 790 sensory neurons per vesicle to be 9.3 Million receptive terminal axons equating to just under 6.45 cm² of base area. We use an identical area to represent the terminus at the pore.

²...or the movement of charged atoms (ions) in space, as is common in biological systems
³\( j_{\text{displacement}} \) is the current density, \( \epsilon \) is the permittivity of the medium, and \( E \) is the field intensity

The electrode plate is constructed from an FR-4 fiberglass substrate with a 1oz. copper lamination milled to dimension. The copper is then coated with a room-temperature vulcanizing silicon sealant to insulate it from direct conduction into the seawater emulating the glycoprotein gel of the natural organ [5].

3.1 Metal Plate Transconduction Experiment

Transconductance, \( G_m \), is the expression of induced current in the output caused by Voltage present at the input. In applied terms, we use a Voltage to establish an electric field, which, in turn, causes a current to flow.

\[ G_m = \frac{I_{\text{out}}}{V_{\text{in}}} \] (5)

To further our suggestion that transconduction is more dominant than direct radiation in conducting media, we devised an experiment in which the electrodes were placed flat against a metal sheet that was coated with an insulating material (a latex paint) to make it non-contact conducting.

The experimental setup was driven by two Universal Software Radio Peripherals (USRP) [8] connected to two different computers. The two computers ran from independent batteries in order to isolate the systems from each other. Additionally, both USRPs feature a LFRX and LFTX daughter card. These receivers and transmitters allow frequencies from DC to about 30 MHz. For data reported in figure 4, a center frequency of 8 MHz, GMSK encoding, and a data rate of 250 kbit/s was used. GNU Radio [2] software was used to control and coordinate the trials.

The results of the experiment appear in figure 4. In the left column of the figure the plates are separated horizontally and in the right column vertically, as shown in the upper photographs.

The behavior appears to be that of two capacitors in series where the transmitting electrode plate couples through electrostatic (e.g. capacitive) action into the conducting body which conducts the momentary current like a wire to the receiving capacitively-coupled electrode plate. As the electrode plates are slid apart, the attenuation decreases as a linear function of the distance. This was observed in the lower left panel of figure 4.

If a plate is separated vertically from the conducting body, as was achieved here by stacking sheets of paper beneath it, the signal strength degrades rapidly. Equation (6) is the transfer function for a load AC-coupled through a parallel-plate capacitor, where the \( \epsilon \) terms represent the dielectric,
Figure 4: Electrostatic transconduction demonstrated in a metallic plate. (left) Horizontal translation along the plate and (right) vertical translation above the plate.

Figure 5: Deployment test in Will Roger’s State Park, California.

$R_L$ represents the load, $A$ is the area of each electrode, and $d$ is the separating distance between the corresponding electrodes or, in this case, between each electrode and the conducting body.

$$H(j2\pi\omega) = \frac{R_L}{\epsilon_r\epsilon_0 \frac{1}{2\pi f_j} + R_L}$$  \hspace{1cm} (6)

From inspection we expect the signal to decay at at least a rate of $1/d$ – the rate at which the effective source impedance increases – with respect to vertical separation. This was observed in the bottom right panel of figure 4.

3.2 Ocean Deployment

After the successful metal plate experiment and laboratory tank testing an expedition was undertaken to evaluate the artificial ampulla design in the Pacific Ocean. Two sites were chosen, one in Will Rogers State Park, near Santa Monica, California (figure 5), and one in Marina Del Rey, California (figure 6) for their proximity to infrastructure and vehicular accessibility.

In order to completely isolate and submerge the transmitting and receiving systems, we designed and implemented a waterproof computer system (figure 6) which encapsulated the prior experimental setup hardware (USRP, TXLF, RXLF, Battery, Hard disk, et. al.) replacing the computer with a single-board variant based around the Intel Atom dual-core 1.6GHz 330 model CPU.

Figure 6: WURI underwater

Figure 7: Spectrogram taken in the Pacific Ocean in Marina Del Rey, California.

The Artificial Ampulla (AA) was attached to this computer through a water-tight bulkhead via a twisted-pair feed line to minimize RF leakage and ensure complete dielectric submergence. This feed line is visible in figure 6 just above the enclosure. A 20MHz wide chirp signal was transmitted from a completely submerged unit through its attached AA to an identical receiver AA located just below the surface and then fed out to a computer system positioned dockside (not submerged to allow for experimental control and monitoring). Figure 7 is a representative finding from the expedition with no detectable chirp signal above the natural background and self-induced noise floor.

3.3 Revised Design

While our input impedance was sufficiently high, the output impedance was not sufficiently low. Due to the Ohmic nature of the conduction current and the naturally low resistance of the ocean water, establishing a large $I_{out}$ implies providing a large $V_{out}$, which in turn requires a very small source output impedance, $R_s$ (so named, because it is just resistance in the case of conduction currents). As originally designed, the artificial ampulla were a good imitation of the electoreceptive organ (receive), but were a poor emulation of the electric organ (transmit).

To permit imaging, as opposed to the original goal of com-
munication, the receiving electrodes were reduced in size from those of figure 3 to those of figure 14 to better approximate the point detectors of the reference adult male Oman shark. All manner of insulation was removed and the steel electrodes were exposed to the ocean simulant. Despite contact, the input impedance remained unchanged as it was instead provided by the voltage measurement equipment (an Agilent 34410A).

4. WAVEFORM DESIGN

Sorted by spectrum, the electric-field excitation waveforms used by electric fish fall into two broad categories: pulse-type (broadband) and wave-type (narrowband). Most readers are familiar with the popularized "electric" eel (Electrophorus electricus) so referred for its ability to generate powerful electric shocks (in excess of 500 Volts!) which it uses for both hunting and self-defense. These emissions are pulsatile, repetitive, and uniform in polarity.

In contrast, wave emissions are bipolar alternating the current direction between head-to-tail and tail-to-head. The Apteronotus albifrons (black ghost knifefish) is an example of a wave-type electric fish. It is a member of the Gymnotiform order, just like the electric eel4.

Knififishes generate electric fields using a specialized electric organ located in the tail region of the fish and detect disturbances to the generated field with receptors along the body. If the animal were to swim in the conventional manner, by deforming a caudal (tail) fin, the attendant body oscillation would distort the sensor array superimposing external field disturbances (prey and predators) on self-induced swimming oscillations. Consequently, Gymnotiforme bodies remain rigid. Propulsion, instead, comes from a long, almost transparent, undulating fin running beneath the body. The rigid body approach makes the fish move like a knife through the water, hence the name.

4.1 Tank Setup

To compare the waveforms, a 55-gallon (∼ 208 liter) acrylic fish aquarium (91 cm × 51 cm × 38 cm) was modified to support further study. The tank configuration is indicated in figure 8. It consists of four electrodes. An excitation electrode, \( P_T \), a neutral electrode, \( P_0 \), a reference electrode, \( P_S \), and an electrode, \( P_C \), mounted on a movable motion-controlled gantry above the tank – as labeled in the figure. All of the electrodes are submerged to an equal depth in the tank of approximately 7.5 cm, while the tank itself is filled near capacity. The current axis runs between electrodes \( P_T \) and \( P_0 \) which are separated by 16 cm. Subsequently, when reporting Voltage measurements, it is to be understood that all measurements are taken at the indicated electrode with respect to \( P_0 = 0\, \text{Volts} \).

The filled water was an ocean simulant constructed from tap-water and iodized salt. The salt concentration was increased until a Marineland Labs, inc. Instant Ocean Hydrometer reported a salt concentration of 28ppt and a relative density (pure water reference) of 1.0205 at room temperature. This is the extreme low-end of the normal range for the Pacific Ocean [13], which creates the intended worst-case scenario for testing.

4.2 Pulse-type EOD

Pulsatile transmission is typically unipolar and consists of sharp rise and fall times. To achieve emulation, excitation using an Agilent E3631A configured as a 10mA current source and operated under computer control was applied. The E3631A was powered on for one minute and then switched off for five minutes moved to the next longitudinal position and the cycle repeated.

The turn-on time of the E3631A was measured into a 50 Ohm load targeting 20mA of load current with 19.2mA average achieved during testing. Under these conditions the average rise time was 4.271ms with a standard deviation of 1.246ms varying over 3.403ms to 6.738ms. The sample size was 100 trials. This closely approximates the rise time of the Brown Ghost Knififish [20].

The results of the experiment appear in figure 10. The lowest surface was recorded from \( P_S \). The recorded values are time invariant, but vary slightly with position reflecting the detection of field variation induced by the presence of \( P_T \). The middle surface is the recorded values from \( P_C \) in which a pronounced temporal decay trend is apparent in the measured Voltage. The E3631A holds current constant so a decay in Voltage corresponds directly to an increase in conductivity. The upper surface is the sum of the lower two surfaces.

This non-linear increase in conductivity is unexpected. Compared with a metallic conductor (wire), conduction through an electrolyte solution is a much more complicated system due to the fact that electrolyte conductivity is dependent on mass transport, not electron transport [10]. As indicated in figure 11, mass transport from the surface of the electrode results in a difference of ion concentration between the bulk
solution and the surface of the electrode ($Fe^{2+}$ ions are generated around the electrode). Without sufficient means to facilitate the rapid diffusion of $Fe^{2+}$ ions, the concentration near the surface becomes larger than that in the bulk solution – resulting in a Voltage between the surface and the solution [4]. This voltage is called the concentration polarization potential and acts to reduce current flow (increase resistance, reduce conductivity).

Alternatively, consider that for the first 50 seconds, the Fe in the electrode is oxidized but remains in the electrode’s lattice structure as the potential is insufficient to overcome the work function and drive the ions from the surface. The positively charged ions collect on the surface layer by layer while negatively charged ions from the solution surround the anode. As the potential difference grows it becomes sufficient to break the lattice and the ions release into the solution. The sudden addition of ions to transfer charge produces a dramatic drop in resistance.

### 4.3 Wave-type EOD

The exact chemistry of the tank system was not explored in detail experimentally, but the outcome is indicative. Constant unipolar currents result in unintended disturbances to the background conductivity of the sea-water. For this reason, both nature and experimental measurements (conductimetry) employ oscillating field potentials to drive these chemical reactions and polarization potentials in both polarities and, therefore, average out their effects.

Our experiment was repeated replacing the E3631A with an Agilent Arbitrary Waveform Generator (AWG) 33220A. The 33220A produces a sine wave at 200Hz and a 10Vpp output through a 50 Ohm output impedance which results in an average of $\approx 225mVAC$ in the water. The results of the experiment appear in figure 12 in which, again, the lower surface represents $P_S$, the middle, $P_G$, and the top, $P_G + P_S$. Notice that all of the surfaces are now time-invariant. The lower density of points in time, as compared to figure 10, is a product of the discrete windowed nature of AC measurement with digital sampling instruments.

### 5. SENSOR DESIGN

With the channel established, the design of the sensor began with a purpose-built physical modeling engine we implemented in Matlab to visualize the electric fields generated and the disturbance that occurs with environmental objects. By abstracting the environment only to relevant net charges (with respect to the background ion concentration), direct analysis becomes computationally practical via:

$$Voltage = \sum_{n=0}^{N_{c}} \frac{1}{4 \pi \epsilon_0} \frac{q_n}{r_n}$$

Where $N_{c}$ is the number of net charges in the environment to consider and $q_n$ expresses the net magnitude of each charge. $r_n$ is the distance between the spatial location under consideration and each specific net charge. $\epsilon_0$ is the permittivity of a vacuum. The equation may be scaled by the relative permittivity of other media for consideration there, but as this has no spatial consequences (only influences magnitude), it is ignored here.

\footnote{While not truly oscillatory, even pulse-type fishes do not maintain DC level for very long.}
If you apply an electric field to a conductor, the mobile charges within it will migrate to align with the field creating a dipole with negative and positive ends and, thus, redistribute the isovoltaic field lines.

In figure 13, we plot comparison traces from simulations and tank trials. If we transect a 2D space along a line parallel and close to the transmit axis, the resulting graph is an x-z plot indicating the Voltage per 1D position. The left pane of figure 13 is a dataset recorded in the actual tank, where the right pane of the figure is the output of our custom simulator which models equation (7). The blue (darker) traces are the tank under background conditions (no targets). The green (lighter) traces were recorded/simulated with the presence of a galvanized steel pipe (located at the position indicated by the black dash in the left pane) under otherwise identical conditions. Note the strong agreement.

5.1 Resolving Self-Interference

The design of a proximity detector requires the isolation of environmental dielectric disturbances (targets) from those self-induced ($P_G$, the probe tip which is on a gantry and moving). The gantry system is a poor substitute for the 15,000 simultaneous sampling channels of the weak electric fish [9] because it physically disturbs the space and must be moved over time resulting in unintended correlation between the spatial and temporal domains.

To mitigate this effect we use the reference electrode, $P_S$, to measure the gantry-to-background self-disturbance and cancel it out through an additive process (the top surface of figure 12).

5.2 Directivity

To enhance signal-to-noise ratio (SNR) and, correspondingly, range, fish attempt to make their EOD’s directional by focusing the current into the region they are most interested in. This is possible because the fish is covered in a skin system that is very electrically resistive. Internally, its physiology maintains a chemistry that is consistent in concentration and uniform in distribution. That, in turn, creates a reference potential that is isolated by the skin from the outside world. The Voltage measurements taken by the sensory organs are a transdermal potential – the Voltage across the skin. This is indicated in figure 2. Because current follows the path of least resistance, if distributed from head-to-tail, it will flow outside around the fish rather than through the fish. By deforming its body the fish can bias the flow of current more heavily to one side or the other.

To evaluate the possibly of mimicking this behavior in our sensor, a Delrin (non-conductive) plate was installed behind the plane of the transmission electrodes at various distances (figure 14). The strength of the resulting field was measured across the long-axis of the tank ($X$ direction) and across it ($Y$ direction). The results appear in figure 15. Within 2cm the effect of the Delrin plate appears to saturate and little additional benefit is achieved from further proximity. At its closest, the gain in detected signal level ($V_{ac,rms}$) versus the absence of the plate is shown in figure 16.

5.3 Results

In order to find small targets and localize them, we must subtract the excitation field by comparing object (target) scans with a background scan. This requires calibration. This is not practical for ocean deployed sensors. In our future work, we expect to eliminate the calibration step by detecting targets through a high-pass filter – e.g. through their real-time disturbance to the background condition as they move around in-range of the sensor.

Five trials were performed with just the background and five with the pipe positioned variously across the tank (the positions of the pipe are indicated by the dots in figure 17). Detection appears highly reliable with the pipe successfully
detected in all five positive trials and successfully not detected in all five negative trials. The detection range of the study was \( \approx 5 \text{cm} \). The position accuracy in the middle of the transmit axis was \( \pm 5 \text{cm} \) after calibration.

6. CONCLUSION

In this work we have discussed the fundamental behavior of an in-ocean electrostatic channel that can be accessed through a low-impedance transmitter and a high-impedance receiver. We have demonstrated the ability to foveate the transmission and localize reception. These qualities were demonstrated in a prototype short-range proximity sensor. Our future work includes the development of a multi-channel array to replace the mechanical gantry and efforts to dramatically increase the detection range.

7. REFERENCES


