Sensing Capacitance of Underwater Objects in Bio-inspired Electrosense

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Abstract—Certain electric fish use a self-generated AC electric field to navigate and hunt. Thousands of sensors on the surface of the fish's body detect the pattern of amplitude and phase distortions of the field, caused by nearby objects. Prior research has suggested that phase distortions may be especially useful for recognition of live objects. Here we present the first study of the utility of phase information in a robotic implementation of active electrosense. Using analytic models as well as our robotic implementation, we investigated how the phase information depends on the frequency of the emitted field, the conductivity of the surrounding water, and object properties. We show that in certain situations phase information enables discrimination between two objects that are otherwise very similar in the amplitude of their electric images. We also show the utility of probing objects with multiple frequencies.

I. INTRODUCTION

Certain species of fish, in two distinct geographical regions (South America and Africa) [13] have evolved the capacity to emit a weak AC electric field and detect distortions of that field for navigation and hunting of prey. This unusual sensory modality is termed “active electrosense.” Active electrosense has been extensively studied in biology [4], [20] as a model system for understanding how sensory signals are processed by the nervous system. Studies have shown that weakly electric fish have separate neural pathways for the phase and amplitude components of electric images [15], [20], [3], [6]. Recently, robotic analogs of active electrosense have been created [17], [18], [1] for use in underwater robot sensing applications as well as for gaining insight into mechanisms of biological electrosense. These prior efforts have focused on obtaining and analyzing the amplitude components of the pattern of field distortions by the sensors scattered over the body surface (the “electric image”). In this study, we focus on the extraction and analysis of the phase component of electric images. A block diagram of our mobile implementation (hereafter “sensorPod”) is illustrated in Fig. 1. One electrode emits an AC voltage while the other electrode is grounded. Sensors along the sides are in differential pairs (marked black) and are used to pick up voltage signals. The essence of active electrosense is to detect minute variations on top of a large signal. In the case of real fish, sensitivity falls in the range of 1:1000–1:10,000 (1.0–0.1 μV on an emitted signal of ≈1 mV) [14], [7]. In our implementation, by subtracting the readings from a geometrically symmetric sensor pair, the common mode signal is canceled, leaving only a small perturbation to be amplified. (The fish does not do common mode rejection.) By demodulating the amplified differential signal with a reference signal from the same frequency source, a sensitive measure of signal amplitude is extracted. Tasks such as wall following and simple object detection can be accomplished using signal amplitude variations [17], [18], [9]. However, if the amplified signal is also demodulated with a reference signal that is π/2 out of phase, both phase and magnitude can be obtained. Such phase extraction is the basis of the current study.

II. PRINCIPLE

A. Dual Channel Demodulation

Our electronics creates an extra phase shift, mostly due to the high pass filter (Fig. 1). We remove this phase shift by use of a rotation matrix: 

\[ \mathbf{R}(\alpha) = \begin{bmatrix} \cos(\alpha) & -\sin(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{bmatrix} \]

\(\alpha\) is calculable based on the analog filter used. If the differential signal to detect is \(A\sin(\omega t + \phi)\), the two demodulated channel readings \(V_{ch1}, V_{ch2}\) are,

\[ V_{ch1} = Gain \cdot A\sin(\phi) \]

\[ V_{ch2} = Gain \cdot A\cos(\phi) \]

Using trigonometric operations and known \(Gain\), the amplitude \(A\) and phase \(\phi\) are separated. In the figures below, “Ch1” and “Ch2” represent these dual channel demodulated and rotated readings.

B. Object Fly-by Profile

Sensory data from two channels yield explicit information about the electrosense signal’s magnitude and phase, encoding the complex impedance of the environment. The impedance depends on a variety of factors including the water’s dielectric properties, the dielectric properties and geometry of objects in the water, and the excitation frequency. Under simplified ideal condition of uniform medium \(\sigma_1, \epsilon_1\), uniform electric field \(\mathbf{E}_0\) and a spherical object of uniform material properties \(\sigma_2, \epsilon_2\), using a polar
coordinate system based on the object \((r, \theta)\) as illustrated in Fig. 2, a closed form analytical solution for voltage perturbation is \([15]\)

\[
\delta \Phi(r) = E_0 \sin^2 \theta \cos \theta \left( \frac{a^2}{r^2} \right) \left( \frac{\rho_1 \rho_2}{\rho_1 + 2\rho_2 + i\omega\rho_1\rho_2(\epsilon_1 - \epsilon_2)} \right)
\]

Here \(\rho\) is resistivity, the inverse of conductivity. As the sensorPod passes by the object to be sensed, the electro-sense reading presents a profile, which we refer to as the “fly-by profile”, as shown in Fig. 2. The zero crossing point occurs at the moment of symmetry as the sensed object passes the position of the sensing electrodes. The peak point in the profile occurs when the sensor pair and the angle \(\theta\) and distance \(d_0\) satisfies triangular equations

\[
\tan(\theta_{\text{max}})d_e = d_0.
\]

This profile is observable in both data channels and is not restricted to the ideal case. The fly-by profile for insulating and conducting objects are different\([18]\). The profiles are broadly opposites of each other. The conductivity contrast factor \((\frac{\rho_1 - \rho_2}{\rho_1 + 2\rho_2})\) in Eq. 3 varies from -1/2 for pure insulators to +1 for pure conductors. Therefore, insulators and conductors with identical geometries will have profiles of opposite polarity and differing magnitude. The phase of the induced perturbation should be 0 for conductive objects and \(\pi\) for insulating objects.

C. Object Phase Spectrum

For capacitive objects, water conductivity and the frequency of the electric field probe are major factors affecting phase. Conductivity influences phase in a relative manner; it is the contrast between water and object conductivity that matters. For natural capacitive objects, like aquatic plants, the less conductive the water is, the easier the object is to detect. For tap water at around 300 \(\mu\)S/cm, aquatic plants appear to be insulating while in water of 40 \(\mu\)S/cm (typical of many South American rivers where electric fish live), aquatic plants are capacitive (for Apterionotus fish with an emission frequency of around 1 kHz.) Probe frequency is also crucial. Frequency is easy for us to manipulate over a wide range. We use a programmable waveform generator and wide-band circuitry. In the biological case, emitted signals typically contain multiple frequency components \([19]\), [2], although it is unclear whether the fish exploits these components for electrolocation.

III. IMPLEMENTATION

A. Hardware Setup

Our experimental platform includes an X-Y robot mounted over a tank \([18]\). The emitting electrodes on the sensorPod were excited by a waveform generator at 4 V peak to peak amplitude with tunable frequency. Only the middle pair of electrodes were used as detectors. The demodulation circuitry is shown schematically in Fig. 1. The demodulation circuit voltage gain is 308. Targets used in experiments include capacitors and resistors with known values, as well as real-world objects such as aquatic plants for which only qualitative electrical properties are known. Capacitors and resistors were mounted on an insulating “holder” and placed in the water. The leads of the electrical component were connected to two electrodes at the bottom of the holder. The effect of the insulating holder itself is fairly large. We therefore subtracted its effect from the electrical images we obtained for the components in the holder. When we studied real-world objects, such as metal, plastic cubes, and grapes, these were attached by a skewer or string whose electric image is minimal and easy to subtract.

B. Fly-by Experiments

Fly-by Operation. Targets were moved by the sensorPod at a fixed velocity and at a fixed distance. Each experiment was run twice, once for the holder or skewer alone and once with the target object also. The holder-alone reading was subtracted from the holder plus target. For example, Fig. 2 shows the fly-by operation with the sensorPod shown as reference. Because of the insulating nature of the object (plastic), there is no phase shift (except for a sign flip of \(\pi\)). The sign flip happens when the object crosses the zero reading point in the
middle but is not shown in Fig. 2. One channel exhibits a sinusoidal-like profile while the other channel is nearly featureless. In wall following tasks, only one channel is used and the relative amplitude is used as the cue to maintaining a desired distance from the wall.

Fig. 3. (A) Dual channel (solid black and dashed red) fly-by profiles of 22 nF and 1 µF capacitors. (B) Phase profile of 22 nF, 50 nF, 100 nF, and 1 µF capacitor, as well as 100Ω and 2kΩ resistors over the range of 20-80mm

Capacitor/Resistor Fly-by. Fig. 3 shows the two channels’ readings of a 22 nF and 1 µF capacitor in our holder at a bath conductivity of 350 µS/cm, typical of tap water. The qualitative difference in phase is easily observed. We measured the phase reading for capacitor and resistor values of 22 nF, 50 nF, 100 nF, 1 µF, 100 Ω and 2 kΩ. All components were scanned from -180 to 180 mm full range (-80 to 80 mm is shown in Fig. 3) and phase reading from within the 20 to 80 mm range is shown. For the trials in Fig. 3, the 20 to 80 mm range is where the readings are bigger, making them more easily interpreted. For both capacitors and resistors, the phase stayed roughly the same over this spatial range. As capacitance increases, the phase decreases and approaches 0. This is because as the capacitance increases, its complex impedance goes down, and it seems more conductive. For resistors, the phase exhibited no change and remained around 0 as expected.

Conductivity and Frequency. Using a capacitor of known value 22 nF, the influence of conductivity and frequency was studied. Fig. 4 shows the fly-by profiles of a 22 nF capacitor under varying bath conductivity and varying frequency conditions. Increased frequency changes the phase of the electric image of the capacitor toward the ideal conductor (zero-phase) situation because higher frequency reduces the complex impedance of the capacitor. The decrease of water conductivity also brings the phase closer to the ideal conductor condition. The reason is that for a less conducting environment, the complex impedance of the capacitor appears to be more conductive. As these measurements indicate, conductivity and frequency are two global parameters that influence the phase of a capacitive object in water. More specifically, increasing probe frequency has qualitatively the same effect as decreasing ambient fluid conductivity.

Real Object Fly-by. As an extension of Fig. 2, cubes of plastic, metal (steel), and fresh meat (lamb) were scanned to show the profiles of objects with diverse properties, shown in Fig. 5. The metal cube used was not anodized but it quickly formed a water-metal interface when submerged [12]. This interface contributes capacitance, making the phase of metal diverge from the ideal conductor case. The fresh lamb gave close to 0 phase similar to a purely conductive object [16]. If compared
with the profile of the plastic cube in Fig. 2, the profile of a purely conductive object is flipped in sign. For a conductive object, one of the channels gives negative reading and then positive reading after it crosses the zero reading point. In the process, the other channel remains zero reading. Fig. 6 shows that a grape is a capacitive object. Its profile changes considerably when the bath conductivity is varied. As noted, frequency and conductivity have the same effect in terms of altering phase, so it is desirable to vary frequency to study capacitive objects.

Fig. 6. Dual channel (solid black and dashed red) fly-by profiles of grape at different conductivity conditions (380 µS/cm and 38 µS/cm). The phase is interpreted with the grape at 50 mm.

Rock vs Aquatic Plant. Here we characterize the electric images of a rock versus a semi-aquatic plant, the ribbon plant (Dracaena sanderiana). The bath conductivity was 40 µS/cm in order to mimic the fresh water environment typical of the native habitat of South American electric fish [11]. Fig. 7 shows the fly-by profiles for the rock and plant respectively. Both profiles have one channel that give very similar readings both in shape and amplitude, while the other channel is quite different for the two objects. This experiment motivates the usefulness of using two out-of-phase channels to perform real world electrolocation tasks. With one channel only, it may be difficult or impossible to discriminate a rock from a plant.

Fig. 7. Dual channel (solid black and dashed red) fly-by profiles of rock and aquatic plant in 40 µS/cm low conductivity water. The phase is interpreted with the objects at 50 mm.

C. Probing With Multiple Frequencies

Operation. To study the frequency response of signals caused by real objects, we used excitation frequencies of 2 kHz, 5 kHz, 10 kHz, 20 kHz, 50 kHz, and 100 kHz. Because grapes are known to be capacitive (due to their membrane) and are easy to mount on a skewer, they were selected as the target object to study frequency, size and distance influence on phase, see Fig. 8.

Probe Frequency. The influence of excitation frequency on phase is evident with spectrum analysis. As shown in Fig. 8, the phase component of a grape’s electric image exhibits significant change over the frequency range we used. At low frequency, the grape appeared to be insulating with close to π phase. As the frequency increases, the phase decreases and crosses π and the signature approaches a perfect conductor. Unlike bath conductivity, frequency is easily adjustable. Thus, frequency scanning is a practical approach to extracting certain properties of objects within the sensory range of electrolocation systems, as will be discussed further below.

Target Distance. A grape was placed at distances of 15 mm and 35 mm perpendicular to the long axis of the sensorPod. The resulting phase and amplitude is shown in Fig. 8A. Distance has no effect on the phase information for this particular object. In future work we will examine how broadly invariance of phase with distance holds across different kinds of objects. In contrast, the influence of distance on the magnitude of the electric image is very pronounced. For objects at the two
measured distances (15 mm and 35 mm), the magnitude profiles increase in inverse proportion to distance.

**Target Size** Two grapes varying in size by 50% were placed at the same location while the frequency was varied. As shown in Fig. 8B, despite this size variation there was very little change in phase over the frequency range.

**Nylon Net vs. Aquatic Plant.** A one-layer nylon screen was rolled into a bundle close to the size of the plant. Its size and that of the aquatic plant were larger than all the previously tested objects. They extended from the surface of the water to the depth of the sensors (Fig. 9A). The purpose of this experiment was to motivate the use of information available when looking at two channels. For the nylon net, both phase and magnitude remain relatively constant over frequency. For the plant, at low frequency it appears to more like an insulator, similar to the nylon net; however, its capacitive properties are revealed as the probe frequency increases. Both phase and amplitude decrease with the increase of excitation frequency for the plant, uniquely differentiating it from the nylon net.

**Grape vs Cherry Tomato.** Grapes and cherry tomatoes of approximately identical geometry were tested to obtain their signal spectrum, see Fig. 9B. The phase spectrum shows a discernible difference and implies the different dielectric properties of two objects. The difference in electric image magnitude is apparent only at high frequency. This is an indicator that geometry is a strong factor on the amplitude spectrum at least for spherical and ellipsoidal objects. We will investigate the influence of size of objects with different shapes in future work.

### IV. Discussion

**A. Analytical Model**

Previous studies [5] have used quasi finite element simulation with lumped elements to study the electric image of objects with complex impedance. [5] used a 2D model and studied the case of electric fish on a cross-section. For our robotic implementation, the field can also be studied computationally using a finite element model. However, a simple model that explains an object’s phase profile is desirable as well. Therefore, rather than solving Maxwell’s equations with boundary conditions [8], we took a different approach by focusing on the electric signal path and using a lumped element model. First, an object is modeled as a certain configuration of lumped resistors and capacitors. Second, the water body is modeled as a resistor, the value of which can be
paths through link resistor \(R_l\). If the object’s complex impedance is smaller, then it lends its path to adjacent paths to reach equilibrium. Fig. 10B gives an explanation of the phase and magnitude spectrum of different objects. \(V_1\) refers to the signal on the side of the sensorPod with no perturbation. It is of zero phase and fixed length. \(V_2\) is the signal that changes with frequency. Its angle increases from 0 to a maximum \(\theta\) and then decreases back to 0 when the frequency is high enough. The difference \(\Delta\) is what is demodulated and analyzed. If the object’s complex impedance eventually goes smaller than that of the water it is replacing, then \(\Delta\) experiences a \(\pi\) phase change from \(\pi\) to 0. And for small perturbation, \(\theta\) is very small. So with approximation, the frequency at which the angle of \(\Delta\) is \(\pi/2\) is also when the object’s complex impedance is the same as unit resistor \(R_u\). This gives an important equation,

\[
|Z_\omega| = R_w
\]

Here \(|Z_\omega|\) is the object’s complex impedance and \(R_w\) is the resistance of the water replaced. The magnitude \(\Delta\) also changes with frequency. As has been seen in Fig. 8 and Fig. 9, the magnitudes at 0 and \(\pi\) \((d_1,d_2\) respectively) are not necessarily the same. The magnitude either decreases or increases as frequency increases. So the modeling of the object in lumped electrical element is a resistor in series with a capacitor and another resistor in parallel, parallel. Fig. 10A. For \(\Delta\) to have \(\pi\) phase change, the resistor should obey these inequalities \(R_u < R_a, R_p + R_p > R_u\). As a result, \(d_1\) and \(d_2\) are functions of \(R_u\), \(R_p\), \(R_u\), \(R_1\), written down as

\[
d_{1,2} = f_{1,2}(R_u, R_p, R_u, R_1)
\]

\(\theta\) reaches its maximum value \(\theta_{\text{max}}\) at a particular frequency denoted \(\omega_{\text{max}}\). This frequency is where \(V_2\) is tangential to the curve \(\Delta\) makes. When the angle variation is small, the comparison between \(d_1\) and \(d_2\) determines the location of \(\omega_{\text{max}}\). When \(d_1\) is smaller than \(d_2\), \(\omega_{\text{max}}\) is smaller than \(\omega_{\pi/2}\). In reality, the single-ended
signal’s phase variation is extremely hard to measure due to noise, which is another reason for using a differential detection circuit. Given that the object is small compared to the sensorPod, \( \omega_{\text{max}} \) can be expressed in terms of lumped elements. Fig. 11 shows the two scenarios of the current path where the object is introduced. In both scenarios, the voltage at the red measurement point (single ended) has one pole and one zero, and the pole and zero are close to each other to generate a small phase shift.

And since zero is less complicated in expression, it will be used as an approximation of \( \omega_{\text{max}} \). When the phase of \( \Delta \) is bigger than \( \pi/2 \), \( R_3 \) represents the resistance in the path that is borrowed. The zero is

\[
z = \frac{1}{R_p C} \left(\frac{R_p + R_s + R_3}{R_s + R_3} - \frac{1}{R_p C}\right)
\]

(6)

Here \( R_4 \) can be expressed as a combination of \( R_u \) and \( R_l \). Also, \( R_3 \) varies with frequency, because it is inverse proportional to the current the object’s path borrows. The more conductive the object is, the smaller the current it borrows, hence bigger \( R_3 \). When \( \omega_{\text{max}} \) is at \( \pi/2 \), \( R_3 \) approaches infinity. When the phase of \( \Delta \) is smaller than \( \pi/2 \), zero is given as,

\[
z = -\frac{1}{R_p C}
\]

(7)

So when \( \omega_{\text{max}} \) is smaller than \( \omega_{\pi/2} \), Eq. (6) is used as the estimation; when \( \omega_{\text{max}} \) is bigger than \( \omega_{\pi/2} \), Eq. (7) is used as the estimation. Using this model with appropriate values of resistors and capacitors, the phase and amplitude profiles of objects were explained qualitatively using circuit simulation tool (SPICE). Also, the previous discussion and associated equations Eq. (4), Eq. (5), Eq. (6) and Eq. (7) were verified as well. The application of these equations for object discrimination will be covered later.

B. Application

Capacitive sensing gives significantly more information than single channel sensing. Fig. 7 shows a simple fresh water environment navigation task. By reading only one channel Eq. 1, the sensorPod was unable to tell a rock from aquatic plant. Object discrimination includes the retrieval of an object’s dielectric strength, its 3D geometry, and distance. It is an inverse problem that is difficult to solve and usually ill-posed [10]. In the spherical object example, the differential voltage has a nice analytical form in which the influence of size, distance and dielectric properties are separated. However, this analytical model has several limitations. First, the field is only strictly parallel to the sensorPod at the middle and the strength varies with distance. Second, even at fixed distance, objects with irregular shapes do not have closed-form analytical solutions, meaning that object shape will also influence the phase. Third, even when an analytical solution is possible, the complex term depends on the composition of the object. Electrosense is diffusive in nature so cubic and spherical objects will have similar profiles given sufficient distance. And as has been observed in experiments, for objects with small aspect ratios, the influence of size and distance is a weak influencing factor of phase and the dielectric property of object is dominated by the magnitude and phase spectrum. Based on this assumption of weak geometric dependency, the object identification problem is broken down into dielectric property identification and geometry identification. For a stationary sensorPod with one pair of sensing electrodes, frequency \( \omega, d_{1,2} \) are measurable. \( \omega_{\text{max}} \) is either obtained by low-noise single ended measurement or by estimation with differential measurement, and \( R_3 \) in Eq. 6 is associated with \( R_u \) and \( R_l \) by a coefficient. Given all this information, the object dielectric property \( R_u, R_p, C \) is expressed in terms of water dielectric strength and used as a reference for object identification. Note that this reference has its limitations. For example, objects of different sizes might appear to be identical in both magnitude and phase spectrum. To further disambiguate the object, geometric information is needed. Geometric information generally requires additional spatial information either from sensor pairs at different locations on the sensorPod or from movement such as a fly-by operation. One extractable feature is the peak location of the fly-by profile. The peak position relative to the sensorPod is associated with both distance and geometry of the object. In the special case of the spherical object, the peak is only determined by distance.

V. CONCLUSIONS

This study concerns the novel and important capacitive sensing component of artificial electrosense. Capacitive sensing, by using an additional demodulation channel, presents additional information that is difficult or impossible to attain from a single channel. Capacitance was shown to affect phase, conditioned on water conductivity and operating frequency. Phase information encodes aspects of the ambient fluid conductivity when considered across multiple frequencies, but is also influenced by target distance and object geometry. Within the background of real-world applications, the usefulness of capacitive sensing was shown. This study also detailed a feature extraction method to retrieve object properties with normalized size and proposed an approach to obtaining distance.

REFERENCES


