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Modeling electric image in weakly electric fish using electrical impedance tomography

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Abstract
In this study, the electrical image of electric fish is modeled via electrical impedance tomography (EIT) using EIDORS, which is a toolkit in MATLAB. The modeling consists of three steps: (1) an 80 cm tank containing water similar to seawater, (2) a fish modeled with 10 electrodes arranged like a fish body, and (3) 1 mA current flow through an electrode and generating an electric dipole field for modeling the field around the fish. To explore the electric image, five important variables in object detection including object distance, position, conductivity, size, and object symmetry and orientation are examined. In general, the analysis of the model indicates that changing each of the variables has an effect on the electrical image. This modeling is able to distinguish between different objects and produce a specific electrical image for each specific object.

Keywords: electric image, electrical impedance tomography, EIT, electric fish

1. Introduction

In freshwater rivers of Africa and South America, some species of fish generate a high frequency and weak electric field (0.1-10 kHz, ≤100 mV⁄cm) around their bodies by the electric organ (EO) which are called "weakly electric fish" [1, 2]. They measure transdermal voltage by thousands of electroreceptor on their skin [3]. The weakly electric fish use this ability for detecting objects with electrical properties different from their surrounding water [4]. When a weakly electric fish approaches an object, fish's electric field is perturbed by the object, as a result, the voltage measured by the electroreceptors is altered compared with the voltage measured in the absence of an object. The "electric image" is defined as the area of the fish's skin where the local voltage has changed [5].

Lissmann and Machin used an electrically transparent porous cylinder containing different types of conductor and non-conductor rods, and trained the electric fish to approach or avoid the cylinder. Thus, they were able to measure detection thresholds by changing the radius of the rod [4]. Bastian showed a range of object detection depends on the size of the fish, the relative amplitude of the electric field and also the object size and impedance. Voltage perturbation decays with object distance rapidly [6]. A large object with very low impedance or very high impedance, causes the largest change in transdermal voltage and can be detected even from far away. But a very small object with impedances similar to the surrounding water is detected only when they are close to the fish [7]. Rasnow measured and simulated the electric image of the sphere and ellipsoid near the electric fish. He showed that the amplitude and shape of an electric image are sufficient to estimate the size, location, and distance of a simple object [2]. Nelson and Maciver in a recording and modeling studies showed that the electric image of a very small object, such as a Daphnia prey-item, can be well approximated as a spherical point and this object project simpler electric images than a larger object [8].

Electrical impedance tomography (EIT) is an imaging technique in industry and medicine, in which a low current (in the order of a few mA) is applied through electrodes on the surface, and the resulting voltage is measured by other electrodes and finally the conductivity distribution of the study space is reconstructed [9]. The forward problem in EIT, given the conductivity distribution σ and the current J injected through boundary electrodes, is to find the potential distribution V in Ω. The solution of the forward problem requires solving the Laplace equation

$$\nabla.(\sigma\nabla V) = 0 , \quad (1)$$

The purpose of the present study is to understand how the electric fish detect the location, size, material, and even shape and orientation of the object or so called electric image by measuring only the voltage. We use electrical impedance tomography to modeling the electric image.

2. Method

In the present study we use EIDORs[1], an open-source toolbox in MATLAB. EIDORs is used for modeling and solving both the forward and inverse problems in the field of electrical impedance measurement and diffuse optics. EIDORs uses finite element method (FEM) for solving the forward problem and calculates the potential distribution. So we use this toolbox for solving the Laplace equation to obtain the voltage disturbance.

Our tank model is then set to be 80 cm by 80 cm in two dimensions. The tank is then divided into triangle elements. The total number of elements is 3200. To match the conductance of the seawater, specific conductance was set to $5.6\ \frac{S}{m}$ [10]. Ten electrodes were used to model an approximately 40 cm long weakly electric fish.

The arrangement of these electrodes is similar to the fish's body. Due to the symmetry, we model only the right side of the fish's body. Here the 10 electrodes are the same as the 10 nodes in the tank grid, and are shown as the green circles in figure 1.

The weakly electric fish, to the first approximation, generates an electric field of a dipole [11]. The first electrode from the left side is the ground electrode and the first electrode on the right side is the current injection electrode. The injection current is 1 mA. Although it is possible to use more complicated stimulation patterns, we chose to keep the location of the current injection electrode fixed just as a weakly electric fish has a fixed location for its electric organ.

At first the electrodes measure the voltages of the tank without the object, then the object is placed in the tank, and the electrodes re-measure the voltages. The voltage difference between the two states shows the presence of the object, which is the definition of the term electric image. Then, we study the effect of different variables on the electric image.

3. Results

To understand the electric image, five important variables for object detection including object distance, object position, object conductivity, object size and object symmetry & orientation were examined.

3.1. Object distance

Detecting the distance to enemy, prey and obstacle is essential for weakly electric fish, thus to investigate the effect of the object distance on the electric image, an object with a circular geometry was placed in the tank. This object had a radius of 2 cm, its conductivity was set to $500\ S$ and the object' distance was changed with respect to the center of the electrode array (figure 2).

Figure 3 shows the voltage disturbance as a function of the distance of the object from the center of the electrode array for each electrode. The magnitude of the voltage disturbances increase as the object approaches the electrode array. As the object get closer to the fish, all electrodes except electrodes 4 and 5 show a decrease in voltage disturbances. Electrode 5 (at the center of the electrode array) measured the maximum voltage disturbances. Far from the electrode array, the voltage disturbances are almost zero.

3.2. Object position

The lateral va-et-vient consists of forward and backward swimming movements, during which the fish's body wall remains at a constant distance from the novel object [12]. For modeling this movement, object similar to the previous section was placed at different positions. The object distance was fixed at 20 cm from the tank's bottom (figure 4).

Figure 5 shows the disturbance voltages as a function of the object position for each electrode. When the object is at the minimum distance from an electrode, that electrode measures the maximum value of the disturbance voltages. Electrode 5 (at the center of the electrode array) measured the maximum voltage disturbance.

3.3. Object conductivity

In the environment of weakly electric fish, there are objects with different electrical properties such as rock and sea grass which fish can distinguish between them. To test the effect of the object conductivity on the electric image, we kept the location of the object fixed with a circular geometry (r = 2 cm) at 20 cm from the center of the electrode array and changed the object conductivity. The tank conductivity was 4.48 S. Figure 6 shows the disturbance voltages as a function of the object conductivity logarithm for each electrode. Since the object conductivity interval is large, its logarithm was used. By increasing the electrode distance from the center of the electrode array, the voltage disturbance reduced. For all electrodes:

if $\sigma_{object} > \sigma_{sea\ water}$ the voltage disturbance is positive,
if $\sigma_{object} = \sigma_{sea\ water}$ the voltage disturbance is zero, and
if $\sigma_{object} < \sigma_{sea\ water}$ the voltage disturbance is negative.

Also for $\sigma_{object} \gg \sigma_{sea\ water}$ and $\sigma_{object} \ll \sigma_{sea\ water}$ the voltage disturbance is constant.

In addition, we investigated this problem whether this modeling can distinguish the internal content of objects. for this purpose, we considered two objects: the first object of a solid sphere with a radius of 4 cm and the second object of the hollow sphere with a shell thickness of 2 cm in the center of the tank (figure 7).

3.4. Object size

One of the important variables for object detection is object size. Thus we placed an object with a circular geometry and a conductivity of 500 S at the center of the tank and changed the object radius (figure 8).

As we expected, by increasing the object radius, the voltage disturbance increased. In this modeling, for $r < 0.2\ cm$ the voltage disturbance approached zero, in other words the electric image is not formed.

[1] Electrical Impedance and Diffuse Optical Reconstruction Software

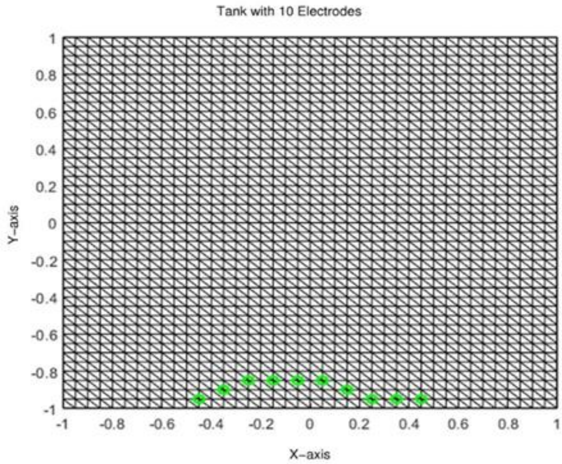

Figure 1. the empty tank model. The tank is 80 cm by 80 cm, divided into 3200 elements. The green circles show the location of the electrodes.

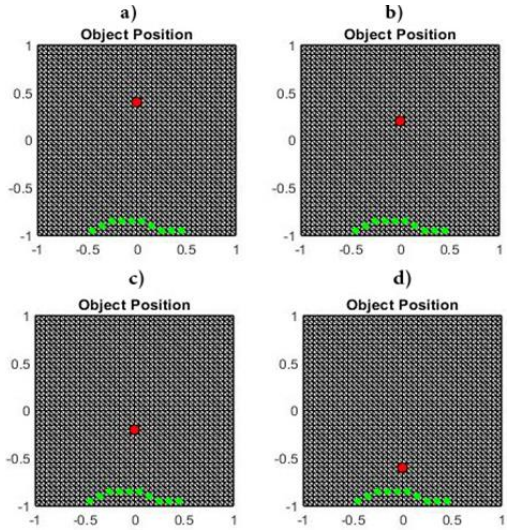

Figure 2. modeling the object at different distances, a) 56 cm, b) 48 cm, c) 36 cm, and d) 16 cm from the center of the electrode array.

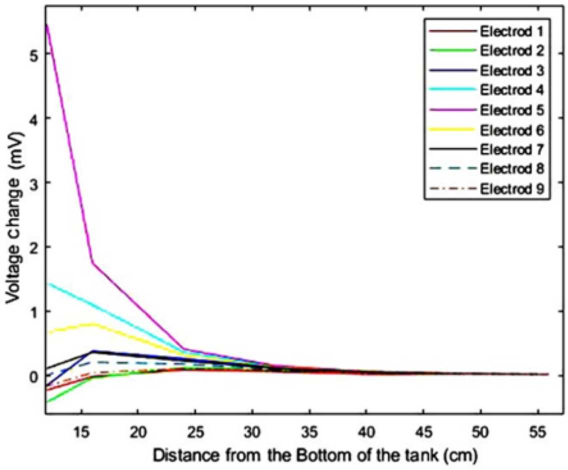

Figure 3. Voltage disturbance of each electrode as a function of the object distance.

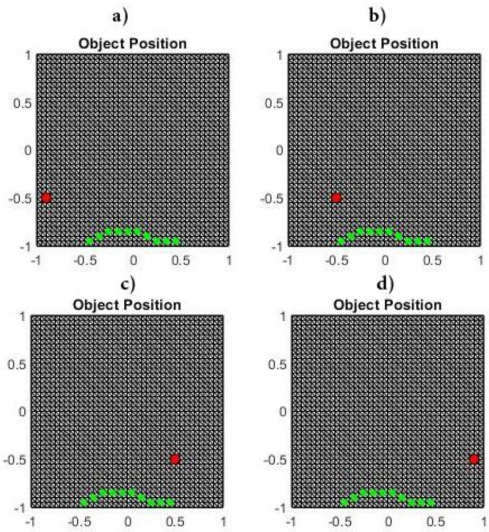

Figure 4 Modeling the object at different positions, a) 4cm, b) 20cm, c) 60cm, and d) 76cm from the left side of the tank.

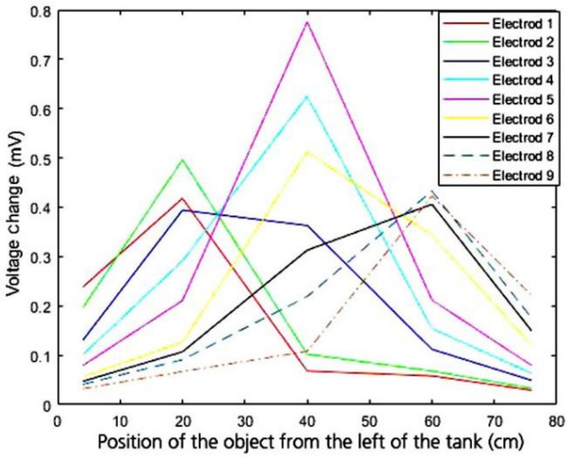

Figure 5. Voltage disturbance of each electrode as a function of the object position.

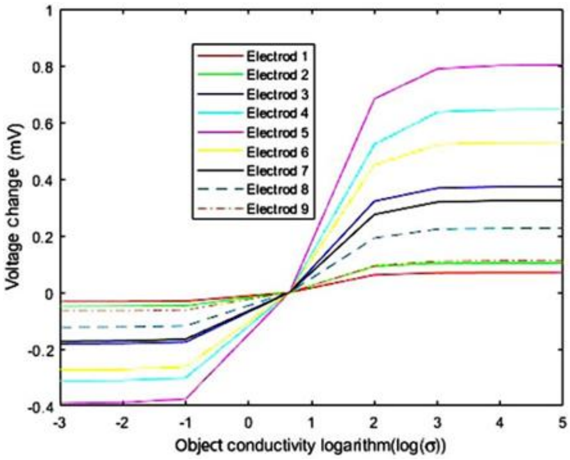

Figure 6. Voltage disturbance of each electrode as a function of the object conductivity logarithm.

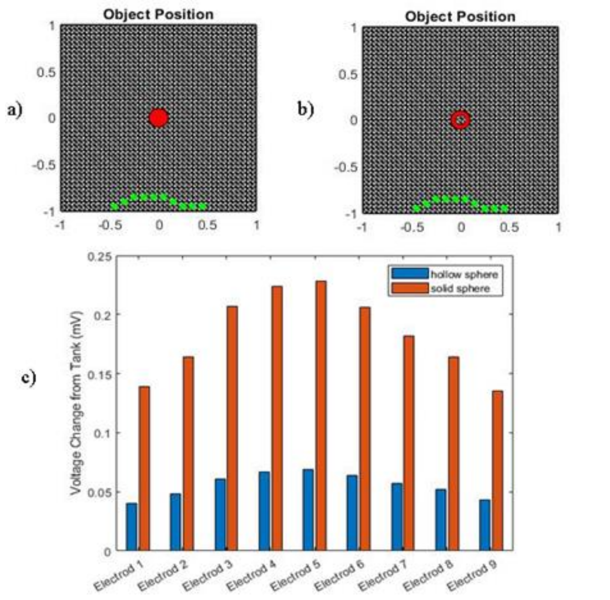

Figure 7. Modeling a) solid, b) hollow sphere. c) Compare voltage disturbance of each electrode for solid and hollow sphere.

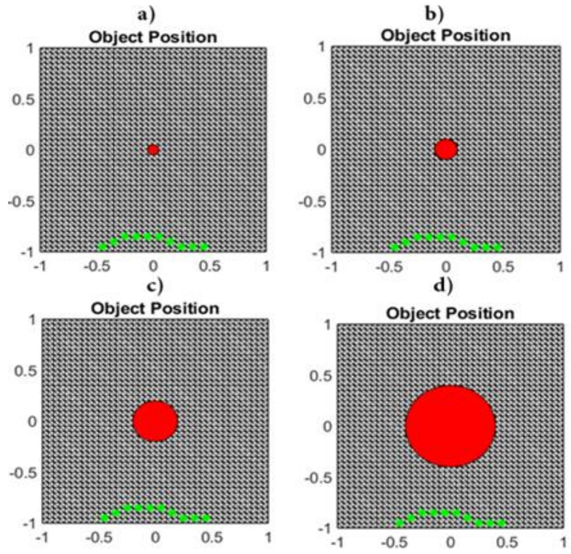

Figure 8. Modeling the object with different radius, a) 2cm, b) 4cm, c) 8cm, and d) 16cm located at the center of the tank.

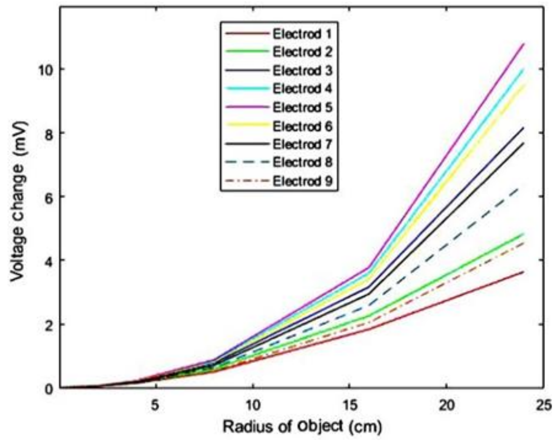

Figure 9. Voltage disturbance of each electrode as a function of the object size.

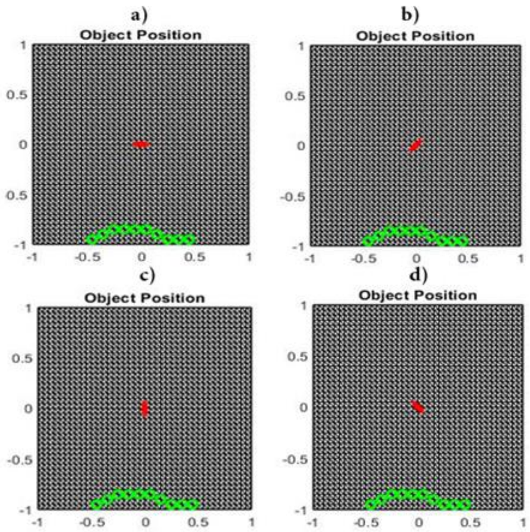

Figure 10. Modeling an elliptical object with different orientations, a) 0°, b) 45°, c) 90°, and d) 135° at the center of the tank.

3.5. Object symmetry & orientation

The objects around the weakly electric fish have different geometrical shapes and often are asymmetric with different orientations towards the fish's body. In this section we investigated the electrical image of an elliptical object (its major radius was 3 cm and minor radius was 1cm) and placed the object with conductivity of 500 S at the center of the tank and changed the angle of the rotation of the ellipse. Figure 9 shows the object's orientations at angles of 0º, 45º, 90º and 135º.

Figure 10 shows the voltage disturbances for different ellipse' orientations. The maximum voltage disturbance is for a horizontal ellipse (orientation of 0°) and the minimum voltage disturbance is for vertical ellipse (orientation of 90°). All electrodes have asymmetric diagrams since the model distinguishes different orientations even 45°and 135°.

Figure 11 compares the voltage disturbances recorded in different electrodes due to a horizontal ellipse, a vertical ellipse, and two spheres with radius of 3 cm and 1 cm. As it is clear from the figure, different voltage disturbances were recorded by all 4 electrodes for these 4 objects. In figure 12 compare voltage disturbance of each electrode for horizontal ellipse, vertical ellipse, spheres with radius 3 cm and 1 cm.

4. Discussion

The purpose of the present study was to understand how electric fish can detect objects around them using

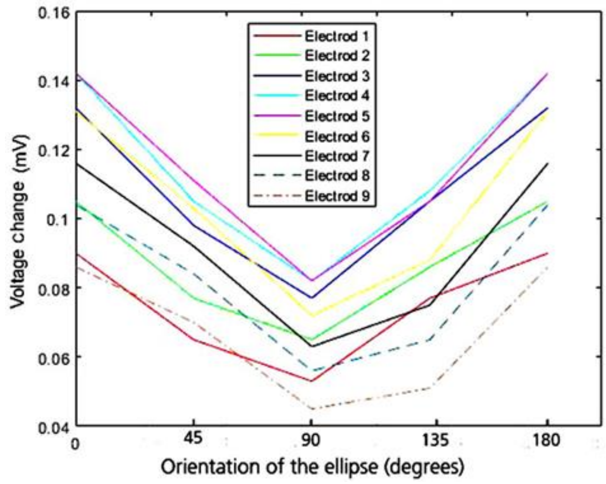

Figure 11. Voltage disturbance of each electrode as a function of the ellipse' orientation.

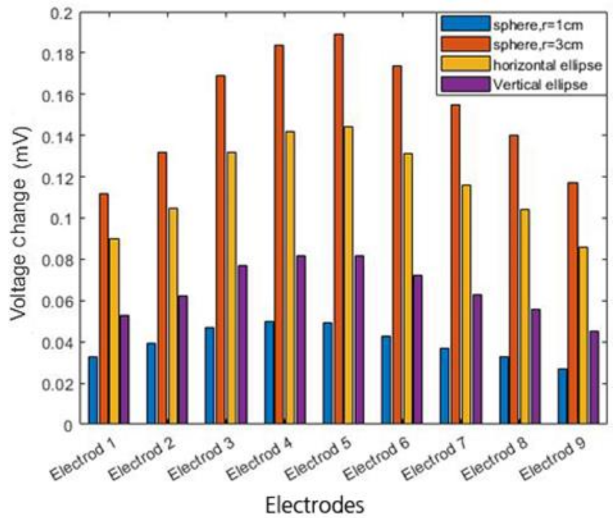

Figure 12. Compare voltage disturbance of each electrode for horizontal ellipse, vertical ellipse, spheres with radius 3 cm and 1 cm

electrical sense. Therefore, we modeled the electric image using EIT and we investigated the effect of object distance, object position, object conductivity, object size and object symmetry & orientation on the electric image. By decreasing the distance of the object the change in the voltage disturbance increased and the resolution of the electric image is better than farther distance that agrees with Bastian's findings that voltage perturbation decays with object distance rapidly [6]. All electrodes except the electrode 4, 5 at a very small distance, the dipole electric field is extremely affected by the object, so by decreasing the distance, the voltage disturbance decreases and it even gets negative, In other words, at these distances, a different electric image is created (figure 3). For different position, the maximum voltage disturbance for each electrode occurred when the object was in a position close to that of the electrode and that means an electrical image center is created in an area of the fish's skin where the object is closed (figure 4). These findings are consistent with previous researches on the effect of object distance on electric imaging [2, 4].

When the object conductivity similar to the environment conductivity, electric field around the fish doesn't change so the object isn't detected. But for object conductivity more and less than environment conductivity the electric field lines passing through the object, respectively, become more and less than the absence of the object and thus the voltage disturbance becomes positive for higher conductivity and negative for less conductivity. We found similar results with von der Emde & Bleckmann's study about object conductivity [7].

The human eye is only capable of perceiving "visible" spectrum and Unable to see very small objects. According to figure 6 fish model only detects objects with limited conductivity and out of this range the voltage disturbance is constant, also in this modeling the objects with $r<0.2$cm the electric image isn't created. But for objects with $r>0.2$cm by increasing the object size the voltage disturbance increased and created the high resolution of the electric image, which is consistent with Nelson & Maciver 's finding that small object project simpler electric images than a larger object [8].

In addition to the distance of the object center to the electrodes, in asymmetric objects with different orientations, the distance of the different parts of the object from the electrodes is also important, because the center of the object is in a fixed point but, for example, for the ellipse horizontal and vertical two sides of major diameter are in different places, have different voltage disturbances and is created their own electric image [2] and different electric image is formed.

In future studies be suggested to be used more electrodes to increase accuracy and get more details about the electric image or use the 3D modeling of the electric fish and investigating the electric image in this case.

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