A Finite Element Method of Electric Image in Weakly Electric Fish

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Abstract. Weakly electric fish can generate an electric field with their electric organ (EO). Through 14,000 electroreceptors distributed on their skin, they can sense the electric field perturbation induced by a nearby prey or object. Many researchers have studied to reveal the mechanism of electrolocalization. Simulations are typically based on an analytical model which represents the EO as a set of charge, or a model based on finite-element method (FEM) in a 2-dimensional space. In this paper, we show a 3-dimensional FEM model to test the electric perturbation of various shapes of objects. Using this model, we show that a measure of caudal relative slope or tail-side half width at half maximum can estimate the lateral distance of a target object regardless of its size, shape and rostrocaudal position.

Keywords: electrolocalization, weakly electric fish, finite element method, relative slope, THWHM.

1 Introduction

Weakly electric fish are able to detect nearby objects in the dark where visual cues are absent. They have a special electric organ which can produce electric potential which are called eletric organ discharge (EOD). Weakly electric fish are able to measure the perturbation of an electric field caused by an object or a prey. In order to understand the mechanism of how the electric fish can sense a target object, an analysis of electric discharge and its effect with a target object has been done. von der Emde et al. [8] did experiments with a pulse type fish, *Gnathonemus petersii*, and has proposed a measure called 'slope to amplitude ratio' that an electric fish might use to measure the distance of a near by object [8].

Chen et al. [2] showed that the electric field of weakly electric fish could be modeled with distributed charges. Their model of electric field is close to real biological data. Electric field perturbation induced by a sphere object near the electric fish could also be calculated by an analytical equation derived by Rasnow [4]. The analytic equation can explain many ideas related to the electrolocation

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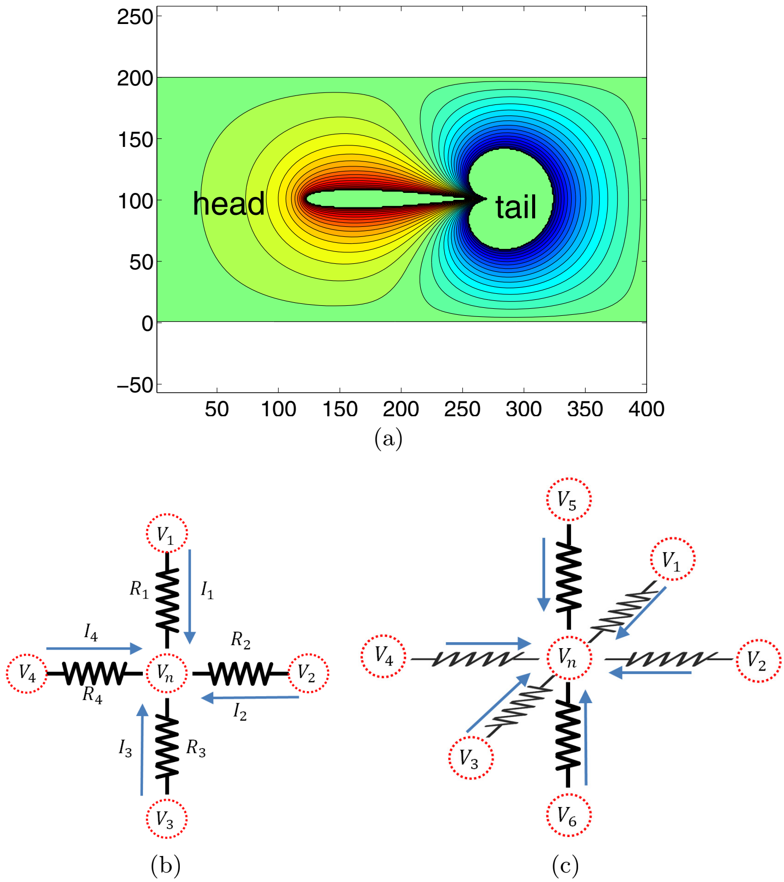


Fig. 1. FEM model (a) electric field generated by an electric fish; the contour lines represent the equipotential lines of the electric field generated by the electric fish (b) a typical FEM model designed in 2-dimension slave; there will be 4 resistors surrounding each element (c) the FEM model designed in 3-dimension space; this is our current model

process of weakly electric fish [5–7]. Through the theoretical model, it is reported that even tail-bending movements can be involved with electrolocation of a target object [5]. However, the analytic model of electric field has its limitation on modelling the field perturbation of multiple objects [7].

The analytical model [2, 4–7] can be applied to a single sphere object. It also assumes that the electric field passing through a target object is constant [4], and it has a simple model over the relative resistance on the internal body of a fish, the skin, and the water. The analytic model can only be applied to a sphere object, not cubes or other shapes of objects. As an alternative, a finite element method can be tested over various shapes of objects or multiple objects. A 2-dimensional FEM model has been used to find the electrosensing property of weakly electric fish [3], but it is not a realistic model for electric fish.

In this paper, we test a 3-dimensional FEM model of electrolocation procedure of weakly electric fish. Our model has an advantage over the previous analytical models; the electric field perturbation can be simulated even for an arbitrary shape of target objects. As an electrolocation measure, the relative slope or full-width at half-maximum (FWHM) can be used [1, 2, 6, 7]. We found that the caudal slope or tail-side half-width at half-maximum (THWHM) in an electric image provides a cue to estimate the lateral distance of a target object. In this paper, we will see how much those measures will be robust for sphere or cube objects at different distances with the 3-dimensional FEM model.

2 Method

2.1 3-Dimensional Model of Electric Fish

The electric organ can be modeled as a set of distributed poles. [2, 6, 7].

$$V(\overrightarrow{x}) = \sum_{i=1}^{m} \frac{q/m}{|\overrightarrow{x} - \overrightarrow{x}_p^i|} - \frac{q}{|\overrightarrow{x} - \overrightarrow{x}_n|} \tag{1}$$

where $\overrightarrow{x}$ indicates an arbitrary point in space represented as a vector, q is the normalization constant of point charge (mV cm), and m is the number of poles (m=155). In our FEM model, a mesh of resistors are given as shown in Fig 1(b)-(c). The distributed poles (which represent the electric organ) are represented in the FEM model as a series of elements which have constant voltage values (voltage source). The size of the water tank used for simulation is 40cm×20cm×20cm, where each size of each gridpoint is 1mm×1mm×1mm (total 16,000,000 elements are available) .

Using the fact that the total amount of the current that comes in or out from one element is zero by Kirchhoff's law, a linear equation is given for each element. To measure the electric field perturbation caused by an object, the base potential on the skin is initially calculated without an object, which is only influenced by electric poles. Then the object perturbation voltage is compared with the base potential.

By using a set of equations assigned to each element in the FEM model, the electric field perturbation can be measured at the electroreceptors on the skin. The transdermal voltage difference forms an electric image.

2.2 Relative Slope and THWHM

Electrolocalization procedure estimates the rostrocaudal distance and the lateral distance a target object near the electric fish. Many researchers have suggested electrolocation measures. von der Emde et al. [8] proposed a slope-to-amplitude ratio in an electric image, and Chen et al. tested a full-width at half-maximum for the lateral distance [2].

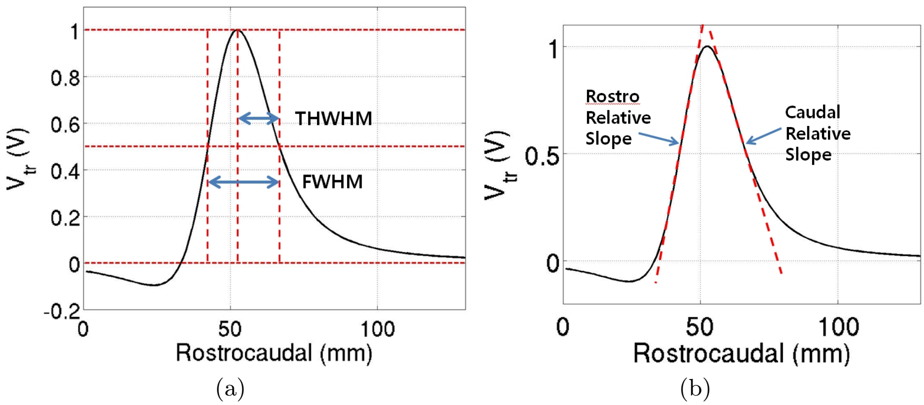


Fig. 2. Measure used in electric images (a) FWHM and THWHM (b) relative slope (rostal and caudal side)

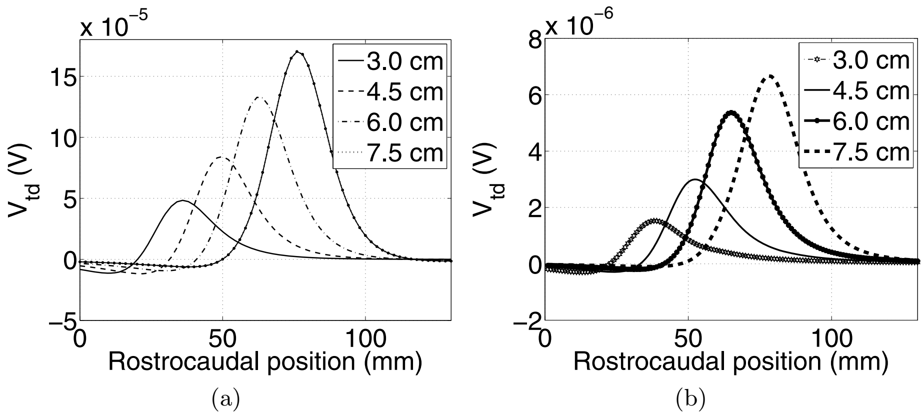


Fig. 3. Transdermal voltages; spherical object diameter: 20mm, lateral distance: 30mm, rostrocaudal distance: 30, 45, 60, 75mm (a) simulation with analytical model [7] (b) simulation with the 3-dimensional FEM model

The slope-to-amplitude ratio can be interpreted as the maximum slope of a normalized electric image which is also called relative slope. von der Emde et al. used the rostral side of the electric image for the relative slope (in other words, the image near the head). Sim and Kim (2012) showed that the caudal slope provides a cue to estimate the lateral distance, regardless of the rostrocaudal position of a target object [7]. In this paper, we will test a new style of measure THWHM, tail-side half width at half maximum (caudal slope) and the caudal relative slope in an electric image. THWHM checks the half-width of the caudal

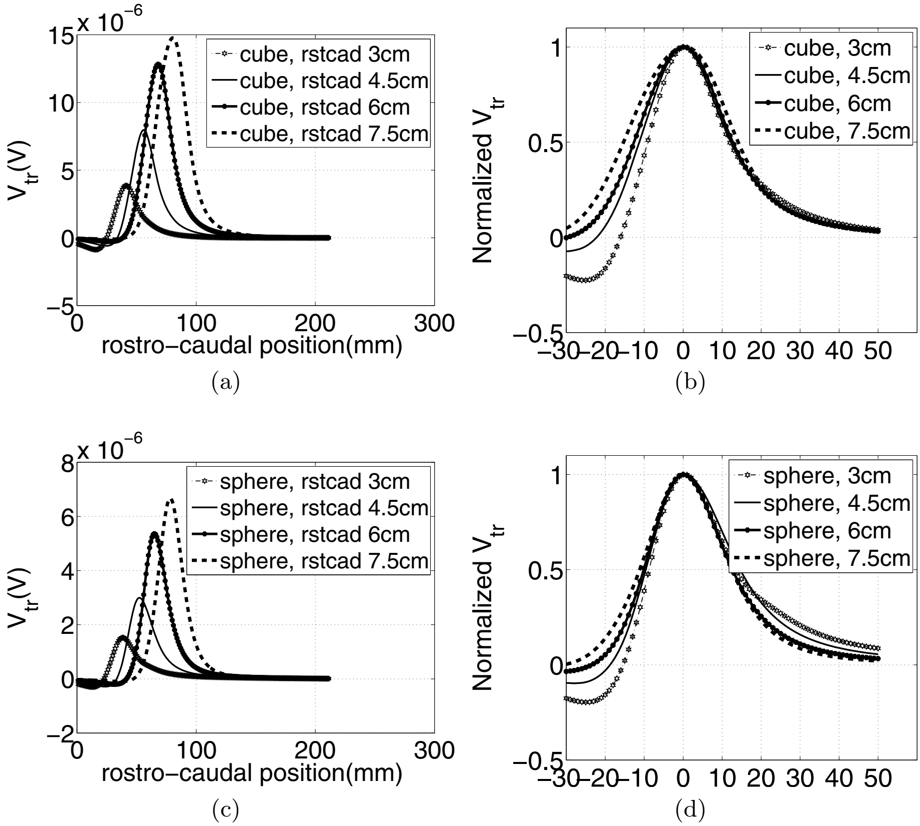
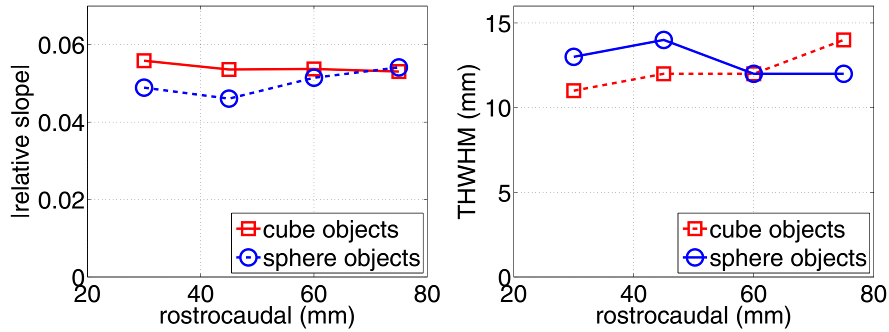


Fig. 4. Simulation results with cubes and spheres (a)/(c) is the electric image for the case of cube/sphere. (b)/(d) shows the normalized electric image where the rostro-caudal location, when peak value occurs, is set to zero. While the rostal side of the slopes vary quite severely, the caudal side shows a similar pattern. This means that the relative slope or THWHM on the caudal side may be used as a measure to estimate the lateral distance, while the relative slope on the rotral side will probably not.

side at half-maximum of an electric image, rather than the full width – see Fig. 2. The caudal slope measures the relative slope at caudal side of the electric image.

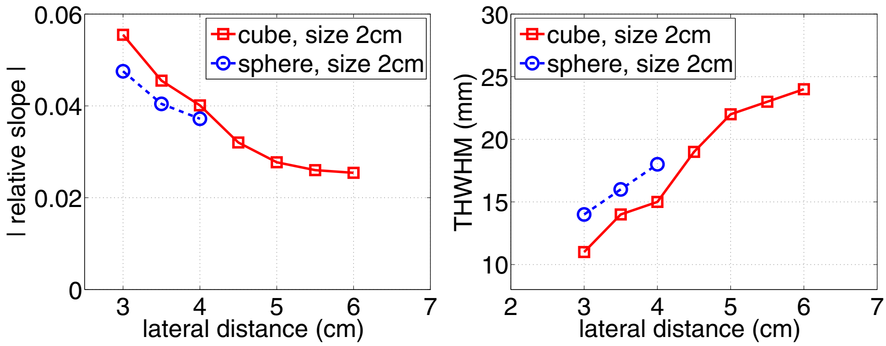
3 Experiments

We first tested two methods, analytical model [7] and the FEM model over a sphere object to validate the FEM model. As expected, the two approaches have the same style of electric images over varying positions of a target object as shown in Fig. 3.



(a) (b)

Fig. 5. Comparison cube and sphere with various rostrocaudal distance (a) relative slope for metal cubes and spheres; even as the rostrocaudal distance of the objects vary, the relative slopes have relatively small transitions (b) THWHM with the same image



(a) (b)

Fig. 6. A cube or sphere simulated under a fixed rostraocaudal distance; cube is 2cm in diameter with fixed rostrocaudal distance, 4.5cm. As the cube's (or sphere's) lateral distance varied from 3cm to 6cm (or 3cm to 4cm) with a 0.5cm interval (a) the relative slope comparison (b) the THWHM comparison.

For our simulation experiments, we placed metal cubes or spheres at a fixed lateral distance and various rostrocaudal distances, and the electric image is shown in Fig. 4. As the object gets closer to the tail, the peak value of electric images increase. This is because the intensity of the electric field is higher in the region near the tail.

Unlike the analytical model [2, 7], our FEM model can simulate the electric image for cube objects. The general trend of electric images for cubes and spheres are similar, but it seems that cube objects make the electric field distorted more severely. We normalized the electric images into the scale [0,1], and we observed much variation on the rostral side of the image. In contrast, the caudal side of the normalized electric image could be a good measure for lateral distance estimation.

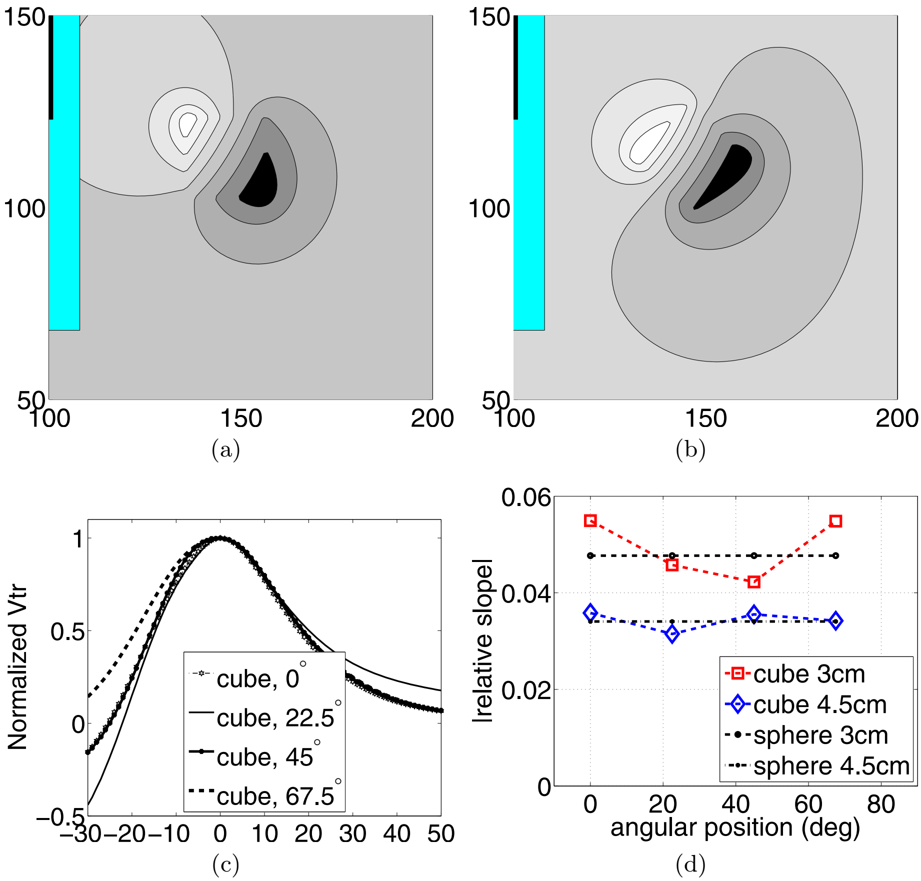


Fig. 7. Comparison of electric images with varying angles and varying distances of cubes. Spheres were also simulated at the same lateral distances for comparison (a,b) figures which represents the voltage perturbation due to a nearby cube. The bar on the left represents the electric fish head region. The cube is rotated with 0 and 45 degrees. (c) normalized electric images of a cube with varying rotation angles (d) the relative slope (on the right side of the image) for cubes varying lateral distance and rotation angle. For each lateral distance(3cm, 4.5cm), a sphere was placed for simulation.

In Fig. 5, the comparison of electric images for cubes and spheres is shown. Fig. 5(a) shows the absolute caudal slope and the slopes of cube objects is slightly larger than those of spheres. The relative slope has a little change for variation of rostrocaudal positions of a target object. Fig. 5(b) shows the results with the THWHM measure. A little fluctuation of the measure can be found with the measure.

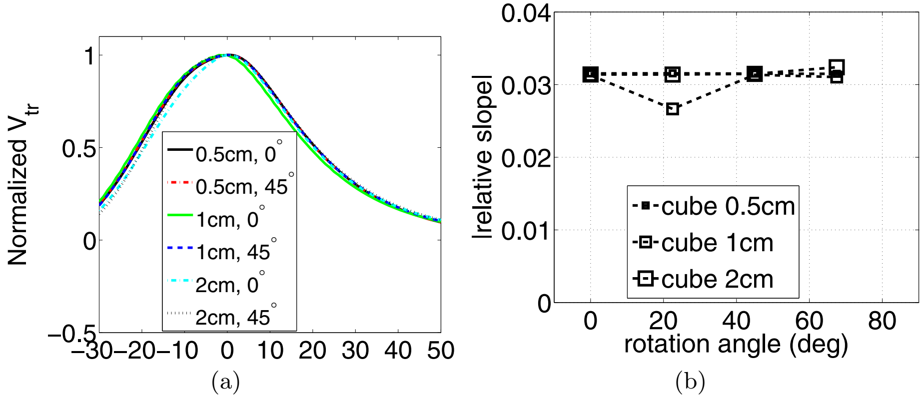


Fig. 8. Electric images and relative slope for cubes with varying sizes and varying angles (the lateral distance and rostrocaudal distance of the objects were fixed to 4.5cm, but the cube sizes and rotational angles varied) (a) normalized electric images (only with rotation angle 0 and 45 degrees and cube size 0.5cm, 1cm and 2cm; total 6 cases displayed) (b) relative slope for all cases (12 cases displayed)

As an object gets closer to the electric fish, the electric image has a sharper curve which means that the relative slope increases and the THWHM decreases. Interestingly cubes and spheres have different values at the electrolocation measures. The electric fish may perceive a sphere to be a little further away compared to the same sized cube, since the relative slope of a cube at a fixed lateral distance is larger than that of a sphere. This result is consistent with the biological experiment result by von der Emde et al.[8].

We check how the electric fish senses cubes at different angles. We used a cube whose side length is 2cm, located at the rostrocaudal position 4.5cm from the head, and at varying lateral distances, 3cm and 4.5cm . We tested the rotation angles, 0, 22.5, 45, 67.5 degrees. For comparison, a sphere for each lateral distance was also simulated. In Fig. 7(a)-(b), the voltage perturbation due to the cube object is shown (at a lateral distance of 4.5cm). The electric images depending on rotation angles of cubes are displayed in Fig. 7(c). The rostral side images have relatively more variation. The caudal side of the electric images are considered for the lateral distance estimation. Fig. 7(d) shows the results with the caudal relative slope. The relative slope of the spheres were given as a reference. From this result, the rotating angle of a cube influences the electric image pattern. However, the overall pattern clearly shows that the closer the object is, the larger the relative slope becomes, regardless of the shape or rotation angle. The fluctuation of relative slope is larger when the object is closer to the electric fish.

Fig. 8 shows another simulation results with varying sizes of cubes. The cube width is either 0.5cm, 1cm or 2cm. Fig. 8(a) is result of the normalized electric images, shows the relative slopes with varying sizes of cubes or rotating angles. The relative slope has only a small change for rotating angles and size variations of cubes at a far distance.

4 Conclusion

Our 3-dimensional FEM model shows similar results with the analytical model [7], and we can test various object shapes or multiple objects. When we investigated the electric images of cubes or spheres, we confirm that caudal relative slope can be a cue for the lateral distance of a target object, regardless of the rostrocaudal position, as Sim and Kim [7] suggested the measure for a sphere object. In our simulation experiments, the caudal relative slope or THWHM gives an approximate estimation of lateral distance even for a cube. The rotation angle of cubes might influence the electric field perturbation, but it seems that cubes at relatively large distances may have a minor effect on the perturbation.

Here, we have simulated the electric image for cubes and spheres at varying distances. To validate our FEM model, physical experiments could be done in the future. Our FEM model can consider the relative resistivity of fish's internal body, fish skin, and water, and so this model has great potential of application. In this paper, we tested a single object, but we can test multiple objects and their interference in the electric image for the future works. It might even be possible to accommodate skin capacitance or object capacitance into the model and measure phase shift of EOD waveform. We still need further work to improve our model. As this model could become more accurate, it might give a crucial key to understanding the mechanism of the electrolocalization. This model could also help one to develop an artificial sensory system, since it could predict the electric potential field in more realistic situations.

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