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Modeling Electrosensory System of Weakly Electric Fish

Miyoung Sim and DaEun Kim

Biological Cybernetics Lab
School of Electrical and Electronic Engineering,
Yonsei University, Schinchon, Seoul, 120-749
(Tel : 82-2-2123-5879)
(daeeun@yonsei.ac.kr)

Abstract: Weakly electric fish have specialized sensory system to detect the electric field. They generate the electric field with the electric organ and sense the intensity change of the electric field with their electroreceptors. If there is a target object in the environment, the electric fish detect the distortion of electric field, caused by the target object. A set of sensor readings in the rostrocaudal line or the dorsoventral line provides the localization information of a target object as well as the object features such as the material and shape. We model the electrosensing mechanism of the weakly electric fish for possible application to the underwater robot. It will be shown how the electric pole distribution in electric organ affects the electrolocation mechanism. The agent can bend the tail for the body movement and a series of sensor readings in the temporal domain and spatial domain are observed. The temporal change with tail-bending movements can be used to estimate the accurate position of a target object. The relative slope with the bent tail is similar to the original relative slope when the fish body is in the neutral line. Regardless of the position, we can apply the same electrolocation rule. This study helps to develop the electrosensor system and the biomimetic sensory system can be applied to the underwater robotic fish.

Keywords: weakly electric fish, electrolocation, distance measure, tail bending, robotic fish**.**

I. INTRODUCTION

Weakly electric fish are very specialized to electroreception. They have three types of sensor systems, mechanosensory lateral line, ampullary electroreceptors, and tuberous electroreceptors [1-2]. Among the three types of sensors, a large number of sensors belong to tuberous electrosensors which are sensitive to the change of electric field. The tuberous system is used for active sensing and weakly electric fish can detect distortion of self-generated electric field [3-5].

The electrosensory system can be applied to the biomimetic robotic fish. Weakly electric fish can identify the location and characteristics such as size and conductivity of a target object [3-4]. When the electrosensory system is equipped in robotic fish, it is possible to localize and identify the characteristics of a target. The electrosensory system is composed of the electric organ discharge and electroreceptors along the body. In this study, two types of electric organ structure, fish-like multiple-pole distribution and a simplified two-pole model, will be tested for electrolocation.

It is shown that some species of weakly electric fish can use spatiotemporal information to localize a target object, especially with tail-bending movements [6-9]. The relative slope is known as a distance measurement regardless of the size and conductivity of a target [10-12].

Normally the electric organ is composed of many poles [5] and in this paper a simplified electric organ model will be introduced with two electric poles. The two-pole electrosensory system can be a practical model which can be easily realized in the electric fish robot. We study two different electric organ models for the electrosensory system and see how the models influence the electrosensory performance. It is useful to study the temporal sensor response with the electric organ models. The relative slope will be tested for distance estimation, and we will show the change of relative slopes with tail-bending movements. The developed electric organ structure and object localization features can be applied to the electrosensory system of a robotic fish.

II. MATERIALS AND METODS

1. Modeling of the electric field

The electric organ of weakly electric fish can be modeled as a composition of many electric poles. The electric potential at position *x* is calculated as the sum of potential differences generated by each electric pole [3].

$$V(x)=\sum_{i=1}^{n-1}\frac{q/(n-1)}{\left|x-x_p^i\right|}-\frac{q}{\left|x-x_p^n\right|} \qquad (1)$$

where *n-1* positive poles and one negative pole exist [3]. This electric field model is based on Gymnotiformes. In the rostrocaudal line, *n* positive poles are arranged in rows and one negative pole is located in the last point of the electric organ [3-5]. The electric field is the gradient of the electric potential.

$$E(x)=\sum_{i=1}^{n-1}\frac{q/(n-1)}{\left|x-x_p^i\right|^3}\left(x-x_p^i\right)-\frac{q}{\left|x-x_p^n\right|^3}\left(x-x_p^n\right) \qquad (2)$$

The electric perturbation of a simple sphere object is derived as

$$\delta V(x)=\chi\frac{a^3E\left(x_{obj}\right)\cdot\left(x-x_{obj}\right)}{\left|x-x_{obj}\right|^3} \qquad (3)$$

where *a* is the radius and x_{obj} is the center of a target and χ the electrical contrast - 1 for perfect conductor and -0.5 for perfect insulator [5].

When we consider the component normal to the electroreceptor, the transdermal potential is

$$V_{td}\left(x_s\right)=E\left(x_x\right)\cdot\hat{n}\left(x_s\right)\frac{\rho_{skin}}{\rho_{water}} \qquad (4)$$

where $\hat{n}\left(x_s\right)$ is a normal vector at the measured point x_s and ρ resistivity. *Apteronotus albifrons* belonging to Gymnotiformes bends the tail from side to side in a range from 45° to -45° [5]. The arrangement of the electric organ is transformed according to tail-bending movements.

In this study, we established two types of electric organ structures, fish-like multiple pole model and a simplified two-pole model as shown in Fig.1. The multiple pole model is based on the model for real electric fish. The simplified electric organ model has two electric poles, positive and negative. The arrangement is different from the multiple-pole model and sensor readings are affected by the electric organ structure.

The relative slope with electroreceptors along the rostrocaudal line is known as a distance measurement [10-12] and it will be introduced in the next section.

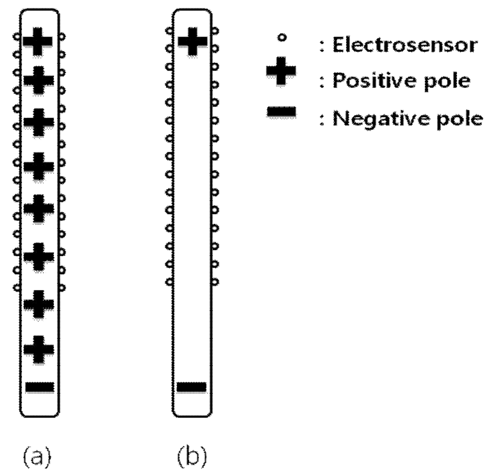

Fig.1. Electric organ models
(a) fish-like multiple pole system and (b) two-pole electric organ

2. Relative slope

The sensor readings can be represented as an electric image. The electric image has been studied to understand the electrolocation mechanism. In this study, the box model is used for electrolocation [13]. The electroreceptors are distributed along the rostrocaudal line parallel to the mid-line of the fish, which is called a box model. The normal vector of the electroreceptor, $\hat{n}\left(x_s\right)$, is vertical to the mid-line of the fish.

In three-dimensional space, weakly electric fish have to estimate the position of a target in the rostrocaudal (from head to tail), dorsoventral (from ventral to dorsal area), and lateral (form fish to side) axis with respect to the fish body. The rostrocaudal and dorsoventral position can be extracted from the maximal point of the electric image [3,5]. The lateral distance changes the intensity and width of the electric image. The relative slope is the ratio of the maximal slope to maximal slope (equation 5). It is possible to estimate the lateral distance regardless of the size and conductivity of a target object.

$$\text{Relative slope }=\frac{\max_i\left\{I\left(x_{i+1}\right)-I\left(x_i\right)\right\}}{\max_i\left\{I\left(x_i\right)\right\}} \qquad (5)$$

The relative slope is a localization feature of a target object in the environment and it is one of essential properties in weakly electric fish as well as artificial robotic fish.

III. Experiments

We applied the relative slope to two electric organ models for distance estimation. Fig.2 and Fig.3 show change of relative slope when the lateral distance and rostrocaudal position of a target object change.

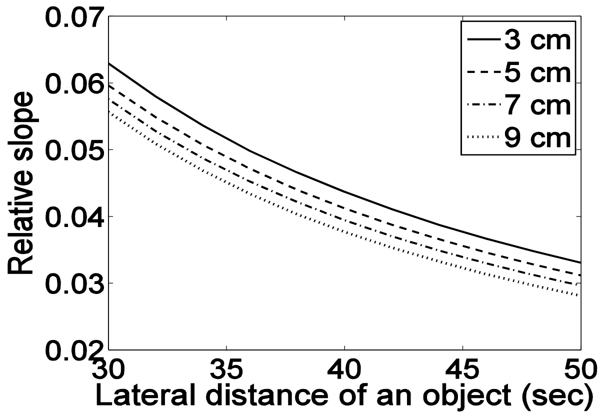

Fig.2. Relative slope for multiple-pole electric organ when the rostrocaudal position of a target changes

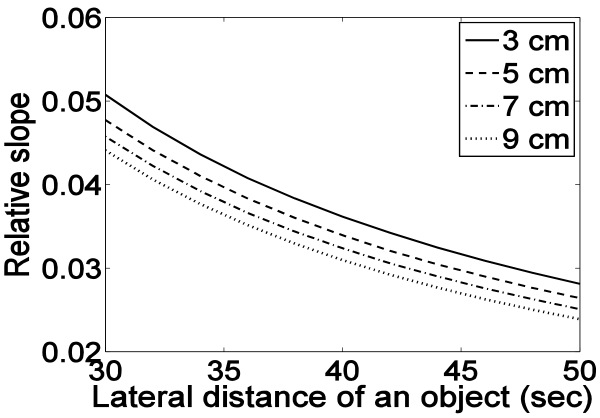

Fig.3. Relative slope for two-pole electric organ when the rostrocaudal position of a target changes

The relative slope is affected by both lateral distance and rostrocaudal position of a target object. When the rostrocaudal position changes from 3cm to 9cm, the shape of the electric image and relative slope are affected. However, the relative slopes in the two-pole system have similar patterns with those in the multiple-pole system when the rostrocaudal position changes. The rostrocaudal position of a target object can be estimated with the peak amplitude in the electric image. Then the relative slope curve can be used for the lateral distance estimation.

We also test the temporal change of electrosensor readings with tail-bending movements. The relative slope is largely independent on the tail-bending movements [8]. The multiple-pole electric organ structure changes the arrangement of the electric poles with tail bending movements. The caudal area of weakly electric fish is approximately 65% of the body length and bends drawing circular portion around the pivot. The radius of the arc is $R=L/2\theta$ where θ is the bending angle. The simplified two-pole model has bending area, 50% of the body length, and this area is bended in a straight line. These two electric organ models have a bending-angle range from 45° to -45°.

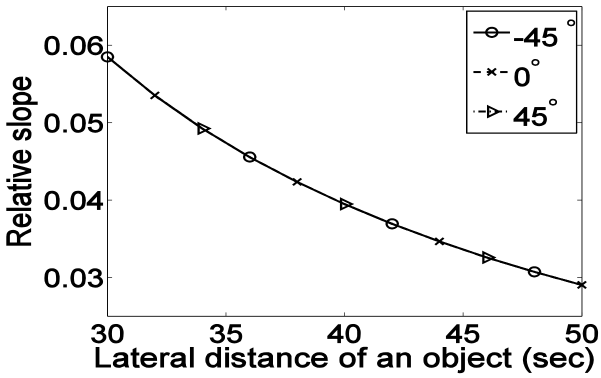

Fig.4. Change of relative slope when the weakly electric fish bend the tail with the multiple-pole model

Fig.4 shows the relative slope with tail-bending movements with the multiple-pole electric organ model. When weakly electric fish bend the tail to the left and right, the relative slope is about the same. Weakly electric fish might use relative slope with bent tail to assure the estimated distance in noisy environment [8].

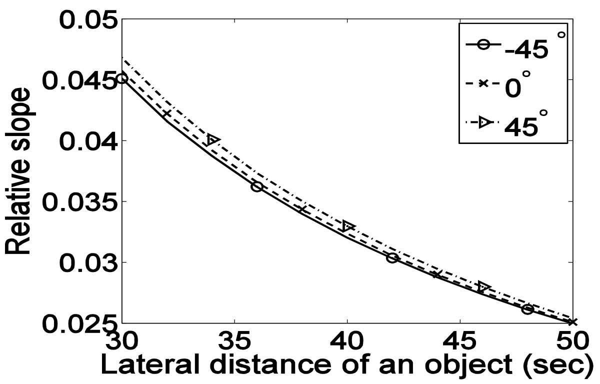

Fig.5. Change of relative slope when the weakly electric fish bend the tail with the two-pole model

Fig.5 shows change of the relative slope when the simplified two-pole model is used. The relative slopes with the two-pole model have a little change, but the patterns are quite similar. We can use relative slope to estimate the distance regardless of the bending angle.

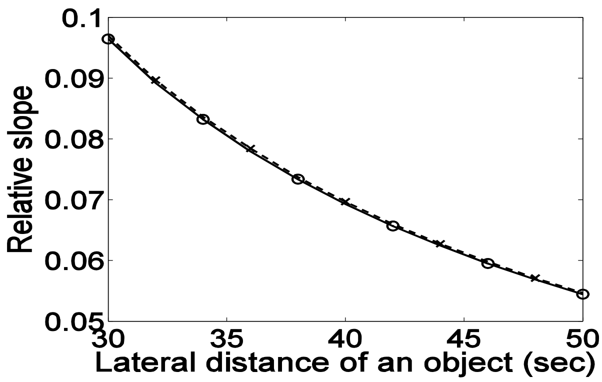

Fig.6. Relative slope with simplified electrosensory model (the marker 'o' is the original relative slope and the marker 'x' the relative slope in integrated electric image with tail-bending)

Fig.6 shows the original relative slope with the fish in a straight line and the relative slope in integrated electric image generated by tail-bending movements. The integrated image calculates the summation of the electric image for each bending phase. In the integrated electric image with the two poles, these relative slopes are about the same to original one. The integrated electric image with tail-bending can more exactly estimate the distance of a target object, which can be useful in noisy environment.

VI. CONCLUSION

In this study, we compared the fish-like multiple-pole model and a simplified electrosensory model with two poles for electrolocation. From the relative slope pattern, we can estimate the location of a target object. Interestingly, the two-pole model shows similar performance of electrolocation as the multiple-pole system, although the two-pole system has slightly more variations in electrolocation.

Weakly electric fish can use temporal structures with tail-bending movements to estimate the estimated distance. When they bend the tail, it is possible to extract relative slope from the electric image and also the temporal integration of sensor readings during the tail-bending movement can be applied to the two-pole system for more exact estimation of target distance. This study shows that we can use a simple electrosensory model with two poles for a robotic fish instead of the complex fish-like multiple-pole model.

V. ACKNOWLEDGMENTS

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