Identifying the Location of a Target Object in the Weakly Electric Fish through Spatiotemporal Filtering Process

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Abstract

The weakly electric fish use their electric organ discharge (EOD) and electroreceptors to identify their prey, explore in their surrounding environment, and communicate with their members in the same species. They are specialized in active electrolocation. They can detect the distortion of the self-generated electric field, which is caused by a target object. There are two types of electric signals, wave-type and pulse-type, that the weakly electric fish can generate. In this paper, we suggest that periodic EOD signals are helpful to extract localization features from noisy electrosensory signals. The cross-correlation between an efference copy signal and the sensory afferent signals in the waveform can produce accurate relative slope in noisy environment. This process has two-phase filtering. The noise-filtering with cross-correlation with respect to the temporal axis and additional filtering with respect to rostrocaudal spatial axis can effectively remove noise, and thus this process provides accurate information of the distance of a target object.

Introduction

Weakly electric fishes localize a target object by their electrolocation system. They are known as only creatures that use active electrolocation with their self-generated electric field (Lissmann, 1958). Electric organ (EO) consists of a modified nerve and muscle cells, and is generally located in caudal area (Kramer, 1999). The EO composed of electrocytes produces an EOD. EODs have waveform characteristics. There are two types of waveforms, pulse-type and wave-type. A lot of Gymnotiformes and all of Mormyriformes (except *Gymnarchus niloticus*) generate a pulse-type of EOD. The pulse-type waveform has short pulses with large intervals between pulses. It is believed that electric fish use a waveform of EOD to recognize another electric fish (Bastian, 1994). In this paper, we focus on the electrolocation of weakly electric fish and an advantage of periodic characteristics of EOD waveform in noisy environment.

There are two types of electroreceptors, tuberous and ampullary electroreceptors (Nelson et al., 2000; von der Emde and Fetz, 2007). These electroreceptors respond to electric stimuli. Usually, ampullary electroreceptors are found in elasmobranch, such as sharks and rays, and they lack in active electric organ. Elasmobranch do not generate the electric field, but just detect the bio-electric signals generated by another creatures. All living animals produce bio-electric signals generated by activation of their muscle and nerve cells. Weakly electric fish have another type of electroreceptors. They detect the change of their own electric signal by tuberous electroreceptors through active sensing (Nelson et al., 2000). About $14,000$ tuberous electroreceptors are distributed all over the body surface of *Apteronotus albifrons*, a species of weakly electric fish. Sensor readings of electroreceptors can provide information to localize their prey, navigate in space, and communicate with conspecifics.

The localization of a target object is very important to capture a prey, avoid their predators, or navigate in the environment. Weakly electric fish produces the electric field and senses the distortion of electric field with many electroreceptors on the whole skin surface. These sensor readings are considered as 'a stimulus image' observed at the set of electroreceptors and it is called 'electric image' (Caputi and Budelli, 2006; von der Emde, 2006). The intensity value of sensor readings are inversely proportional to the distance between a target object and the sensor location on the surface.

When a target object is located near the weakly electric fish, sensor readings of electroreceptors draws a bell-shaped curve. The rostrocaudal (from head to tail) position of a target object can be easily measured with maximal amplitude of an electric image(Rasnow, 1996; Chen et al., 2005). When the target object becomes far away from the electric fish, the maximal value of sensor readings decreases. The maximum amplitude of the electric image is also affected by the size and conductivity of the target object. To measure the lateral distance of a target object from the midline axis of weakly electric fish, the relative slope and full-width at half-maximum (FWHM) have been suggested as a distance measure (Schwarz and von der Emde, 2001; Chen et al., 2005).

If we have a clean electric image without noise, it is not difficult to get the lateral distance by the relative slope or FWHM. The relative slope is the ratio of the maximal slope to the maximal amplitude of sensor readings in the rostrocaudal axis (Schwarz and von der Emde, 2001). The FWHM

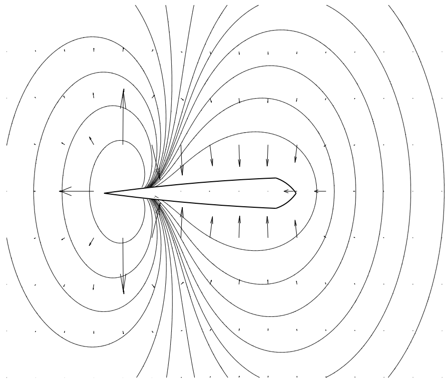


Figure 1: Electric field generated by the EO of weakly electric fish (solid contour lines indicates equipotential lines)

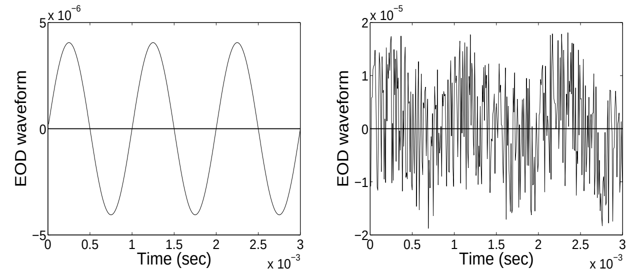
is the width of the bell-shaped curve at half of the maximal amplitude (Chen et al., 2005). The change of electric signal is affected by the size and lateral distance of a target object. The width becomes larger when the size of a target object increases. Thus the ratio between maximum amplitude and width, or the ratio between maximum amplitude and slope can be a cue for the lateral distance without considering another properties of the target object, for example, size and conductivity. However, when electric potentials at the electroreceptors include noisy signals, the preprocessing step is needed to extract noise-free signals. We suggest a method using a waveform of EOD to extract the denoised electric image and measure the lateral distance of a target object.

In the previous researches, it has been pointed out that electric properties of a target object can be measured by the distortion of EOD waveform (von der Emde, 1998). Yet, how to handle noisy signals for the relative slope information has not been studied so far. In this paper, we observe a waveform of EOD to measure the lateral distance, and then the filtering process with respect to time axis as well as spatial axis is applied to obtain noise-free signals. Ultimately we can estimate the distance of a target object very accurately. Here, we use the cross-correlation between an efference copy signal and the sensory afferent signals to obtain the filtered output in the temporal axis and then apply a low pass filter to the output of electroreceptors along the rostrocaudal axis.

Localization of a target object

Fig. 1 shows electric field generated by the EO of weakly electric fish. We use an electric field model of *A. albifrons* which belongs to Gymnotiformes species established by Rasnow (1996) and Chen et al. (2005). The electric field is radically spread to every direction of the body of weakly electric fish.

Gymnotiform fishes generate continuous periodic waveform which has symmetric maximum and minimum point



(a) (b)

Figure 2: EOD waveform (a) original self-generated waveform (b) noisy waveform)

with respect to the zero point (Fugere and Krahe, 2010). Fig. 2 shows the simulated EOD waveform that has frequency $1kHz$. It is known that *A. albifrons* generates such EOD waveforms which have about $1kHz$ frequency (Nelson and MacIver, 1999).

Electric field modeling

The EO is modeled as a collection of electric poles (Rasnow, 1996; Chen et al., 2005). Then the electric potential can be calculated as a total sum of potential from each electric pole. When there are n electric poles, $n-1$ positive poles and one negative electric pole, arranged along the midline of the weakly electric fish, the electric potential, $V(\vec{x})$, derived as

$$V(\vec{x}) = \sum_{i=1}^{n-1} \frac{q/(n-1)}{|\vec{x}-\vec{x}_p^i|} - \frac{q}{|\vec{x}-\vec{x}_p^n|} \quad (1)$$

where $\vec{x}$ is the position of measured position, $\vec{x}_p^i$ the position of i-th electric pole, $\vec{x}_p^n$ last n-th negative pole. The value of q means the normalized potential magnitude which ranges from $8mV$ to $20mV$ (Chen et al., 2005). The total sum of potential magnitude of the whole electric poles including the negative pole should be zero. Thus, the magnitude of a positive pole is q/m and a negative pole $-q$. The electric field $E(\vec{x})$ at the position of $\vec{x}$ is derived as the gradient of the electric potential as

$$E(\vec{x}) = \sum_{i=1}^{n-1} \frac{q/(n-1)}{|\vec{x}-\vec{x}_p^i|^3}(\vec{x}-\vec{x}_p^i) - \frac{q}{|\vec{x}-\vec{x}_p^n|^3}(\vec{x}-\vec{x}_p^n) \quad (2)$$

To consider the component of the incident electric field vertical to the surface of a weakly electric fish, the transdermal potential difference, $V_{td}(\vec{x})$, is calculated as

$$V_{td}(\vec{x}_s) = E(\vec{x}_s) \cdot \hat{n}(\vec{x}_s) \frac{\rho_{skin}}{\rho_{water}} \quad (3)$$

where $\hat{n}(\vec{x}_s)$ is the normal vector at the electroreceptor on the skin, and ρ_{skin} and ρ_{water} resistivity of skin surface and water, respectively.

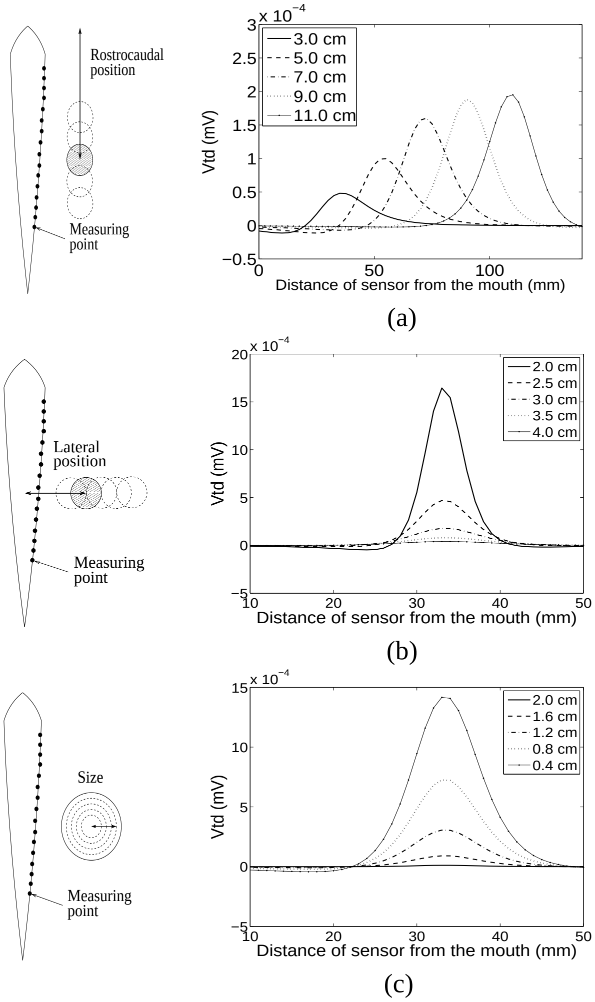


Figure 3: Electric image distorted by a neighboring target object along the rostrocaudal line on the surface of weakly electric fish with varying (a) the rostrocaudal position (b) the lateral distance (c) the size of a target object (modified from (Sim and Kim, 2010))

Rasnow (1996) and Chen et al. (2005) show the effect of a simple spherical object as a targt object. The distortion of electric field caused by a neighbor target object, $\Delta V(\vec{x})$, is calculated as

$$\Delta V(\vec{x}) = \chi \frac{a^3 E(\vec{x}_{obj}) \cdot (\vec{x} - \vec{x}_{obj})}{|\vec{x} - \vec{x}_{obj}|^3} \quad (4)$$

where a is the radius and $\vec{x}_{obj}$ the center of a spherical target object. The transdermal potential difference of an object perturbation $\Delta V_{td}(\vec{x}_s)$ is given by

$$\Delta V_{td}(\vec{x}_s) = -\nabla(\Delta V(\vec{x})) \cdot \hat{n}(\vec{x}) \frac{\rho_{skin}}{\rho_{water}} \quad (5)$$

Electric image

The change of transdermal potential value (equation (5)) due to a target object along the rostrocaudal axis draws a bell shaped curve (see Fig. 3) when the position and size of the object change. It forms one-dimensional electric image. Fig. 3 (a) shows the variation of electric images when the rostrocaudal position of the target object changes. The maximal amplitude of the electric image is found at the rostrocaudal position of the target object. The level of intensity depends on the interaction with positive and negative poles. If the object is closer to the tail, the stronger intensity can be observed for the same lateral distance. In Fig. 3 (b) and (c), the rostrocaudal position of the target object is fixed, and thus the location of the maximum amplitude has no shift, but only changes of maximal amplitudes are observed at a fixed rostrocaudal position. The intensity is affected by not only the lateral distance but also the size of the target object. Therefore, the intensity is not a direct cue for the distance.

In a three-dimensional space, we can consider rostrocaudal, lateral, and dorsoventral axis (from dorsal to ventral side) with respect to the fish body. The rostrocaudal and dorsoventral position of a target object can be determined directly from the location of the maximum intensity. The maximal amplitude can be observed at the point close to the target object. In contrast, the lateral distance can be estimated by the ratio between the maximal value, slope, and width of the electric image.

We use the relative slope to measure the lateral distance of a target object. To extract proper features from noisy signals, we need to consider filtering process. Here, we suggest spatiotemporal filtering process over noisy electric signals.

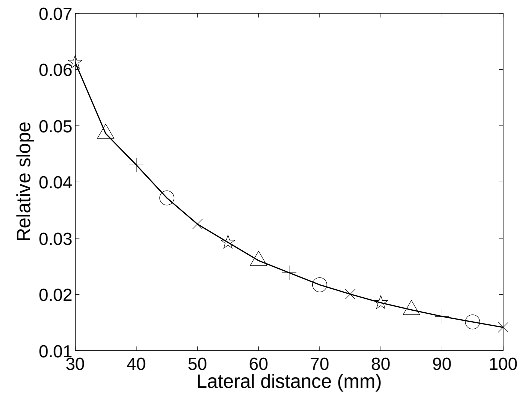


Figure 4: Relative slope when the lateral distance of the target object changes with varying object sizes (each marker represents a radius of 0.4, 0.8, 1.2, 1.6, $2.0cm$) (modified from (Sim and Kim, 2010))

Relative slope

The relative slope is the ratio of the maximal slope to the maximal amplitude of the object perturbation curve (electric image) and it is not affected by size and conductivity of the target object. Fig. 4 shows the change of relative slope when the target object moves away along the lateral axis with varying object sizes. The relative slope is not affected by the conductivity, either.

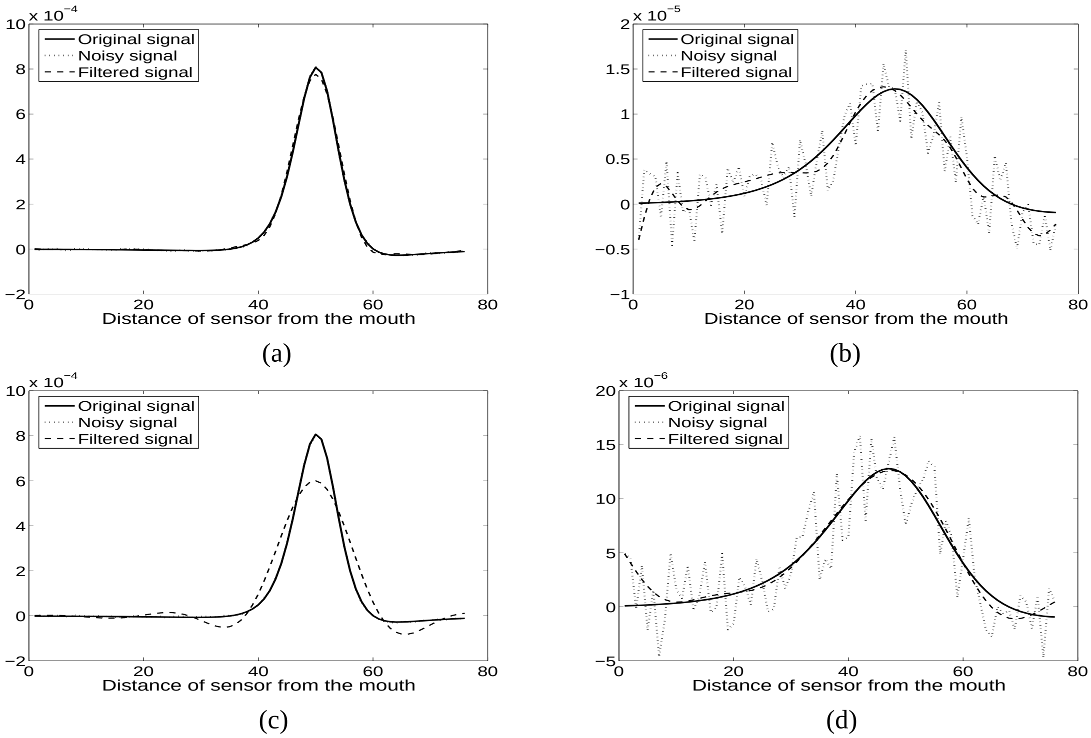


Figure 5: Electric image when noise is distributed uniformly from -5×10^{-6} to 5×10^{-6}; (a) and (c) lateral distance of a target object is $2cm$; (b) and (d) $4.8cm$ (solid : electric image without noise, dotted : distorted electric image, dashed : filtered image with cut-off frequency (a) and (b) 20% (c) and (d) 10% of the spatial sampling rate)

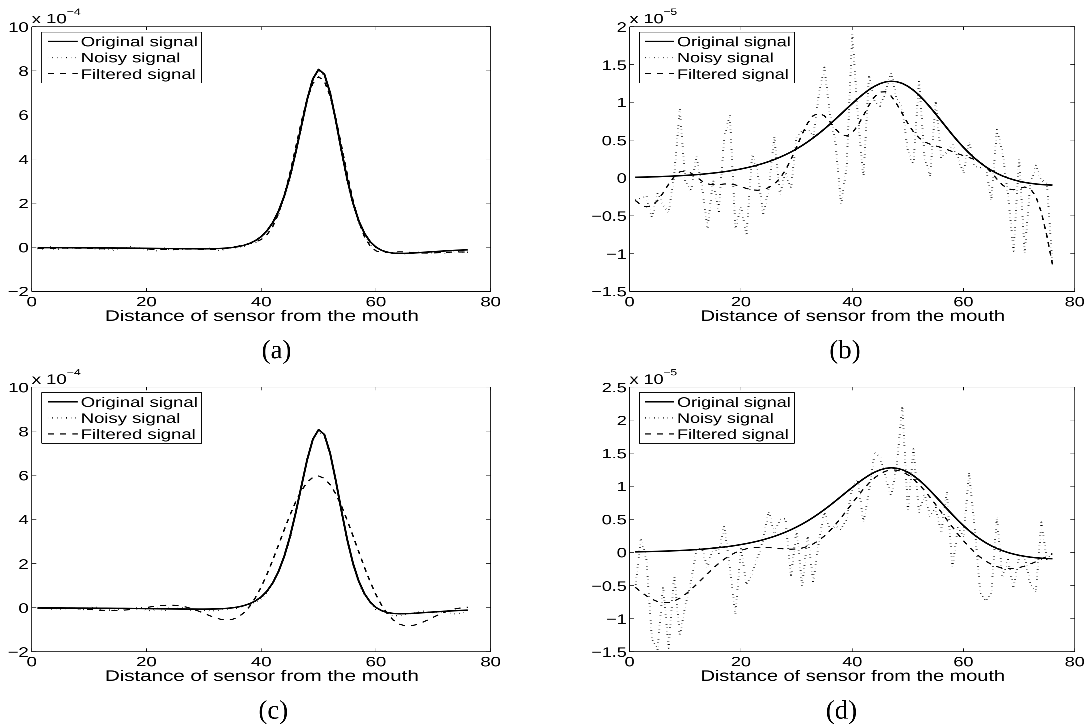


Figure 6: Denoised electric image using low pass filter when there exist Gaussian noise with variance 5×10^{-6}; (a) and (c) lateral distance of a target object is $2cm$; (b) and (d) $4.8cm$ (solid : electric image without noise, dotted : distorted electric image, dashed : filtered image with cut-off frequency (a) and (b) 20% (c) and (d) 10% of the spatial sampling rate)

We use relative slope to measure the lateral distance. However, in the natural environment, noisy signals are inevitably observed in electric images. Pure electric signals of object perturbation are mixed up with noise. It is difficult to estimate the relative slope accurately with the two noisy parameters, amplitude and slope in the electric image. Thus, we suggest a possible noise-filtering analysis over the spatiotemporal sensor readings. To smooth these distorted electric signals, we take two phase of filtering process, cross-correlation with self-generated EOD waveform and low pass filter over a collection of sensor readings along the rostrocaudal axis.

Method1 : Low pass filtering

We use a fifth order butterworth filter as a low pass filter. Generally, the noise has high frequency characteristics. Fig. 5 shows the result of that filter application. The cut-off frequency determines the frequency range of filtered electric signal. The sensor readings of electroreceptors are spatially distributed along the rostrocaudal axis. The filter is applied to the spatial distribution of the electric signals which is the result of object perturbation.

Fig. 5 shows the noisy electric image and the filtered image when the lateral distance of a target object is $2.0cm$ in Fig. 5 (a) and (c), and $4.8cm$ in Fig. 5 (b) and (d). Here, we assume random noise. The range of uniform random noise is 10×10^{-6} and it is about 8% noise level of the maximal amplitude observed when the lateral distance of the target object is $3cm$. The cut-off frequency is set to 20% and 10% of the spatial sampling rate, respectively. When a target object moves away from the weakly electric fish, the intensity decreases radically. With the filtering process, the original electric signal can be hardly restored. In Fig. 5 (b) and (d), the low pass filtering is applied with different cut-off frequencies. The smaller cut-off frequency is more effective to smooth the noisy electric signal, but the filtered signal is a little deviated from the original signal purely depending on the lateral distance.

Fig. 6 shows the noisy and denoised electric images when the noise is modeled as Gaussian noise with variance 5×10^{-6} and zero mean. In Fig. 6, the noise level is about 8% when the lateral distance of the target object is $3cm$. The distortion of electric image is similar to that with uniform random noise. In this case, the cut-off frequency 20% of the spatial sampling rate is appropriate to obtain the desired filter output.

Method2 : Cross-correlation

The self-generated EOD waveform at the tail produces the sensory afferent signals at each electroreceptor. If there is any object near the fish body, the distorted afferent signals can be measured. Reafference cancellation process can be expected in the sensory-motor loop. Here we consider another aspect of motor signal feedback.

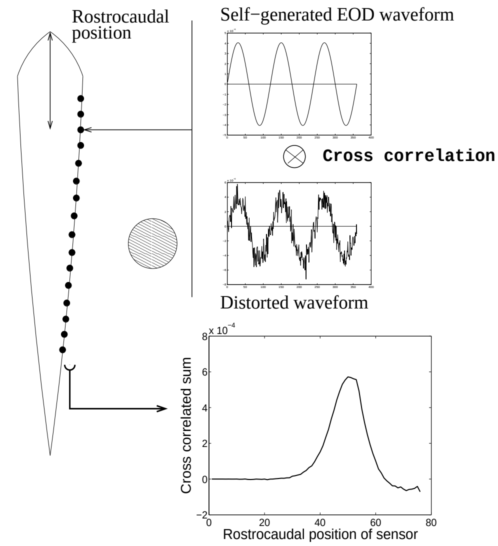


Figure 7: Process of denoising electric image using cross-correlation

The cross-correlation between an efferency copy signal and the sensory afferent signals in the waveform can lead to an interesting feature of noise removal. The cross-correlation equation is given below :

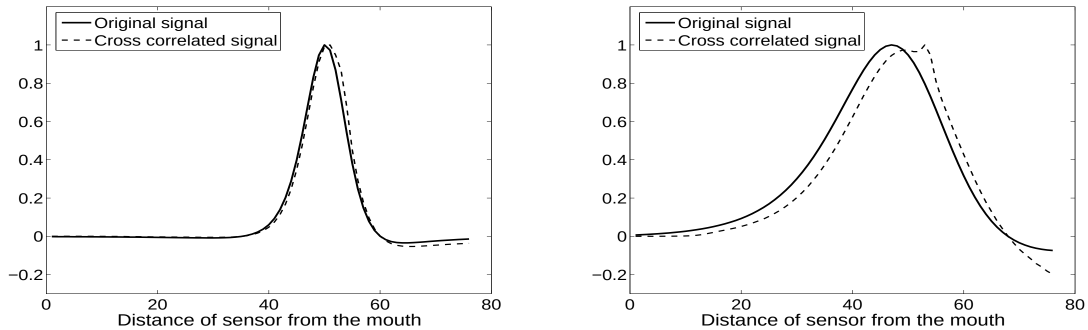
$$a * b = \max_k \{\sum_i a[i]b[k+i]\} \tag{6}$$

where $a[i]$ is the i-th efferency copy signals and $b[i]$ is sensory afferent signal. Normally the cross-correlation has been applied for template matching or for sound localization in the auditory system. We suggest this correlation method can estimate the level of sensory afferents depending on the efference command signals. The electroreceptors can reflect the perturbed signal by neighboring objects. The senosr readings disturbed by other factors should be taken as noise. Thus, the cross-correlation with a sinusoidal waveform of efference copy signals can obtain the noise cancellation. In simulation experiments, noise is modeled as uniform random noise or Gaussian noise to reflect the real electroreception.

Each electroreceptor can process the cross-correlation over the two waveform signals, the common self-generated EOD waveform and the distorted electric signal affected by a target object and noise. Fig. 7 shows the diagram and the result along the rostrocaudal position. Fig. 8 shows the result of the denoised electric signal by cross-correlation.

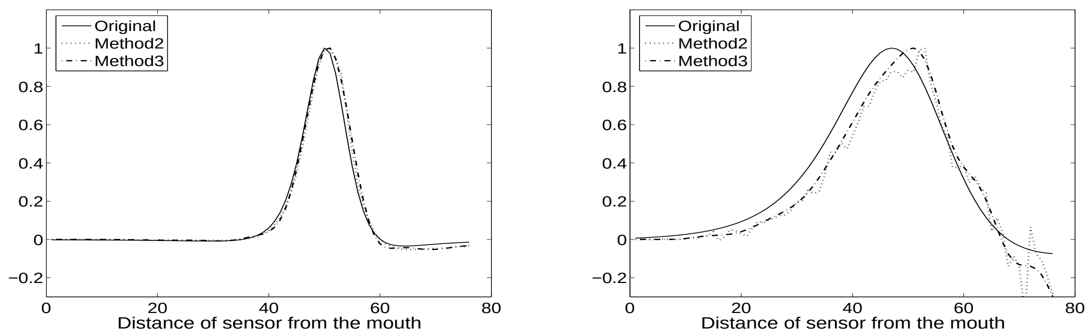
Method3 : Filtering after cross-correlation

After applying the cross-correlation, we obtain noise cancellation for each electroreceptor along the temporal axis. However, the electric image is still noisy along the rostrocaudal line. For accurate localization of a target object, we need to calculate the relative slope, that is, the two param-



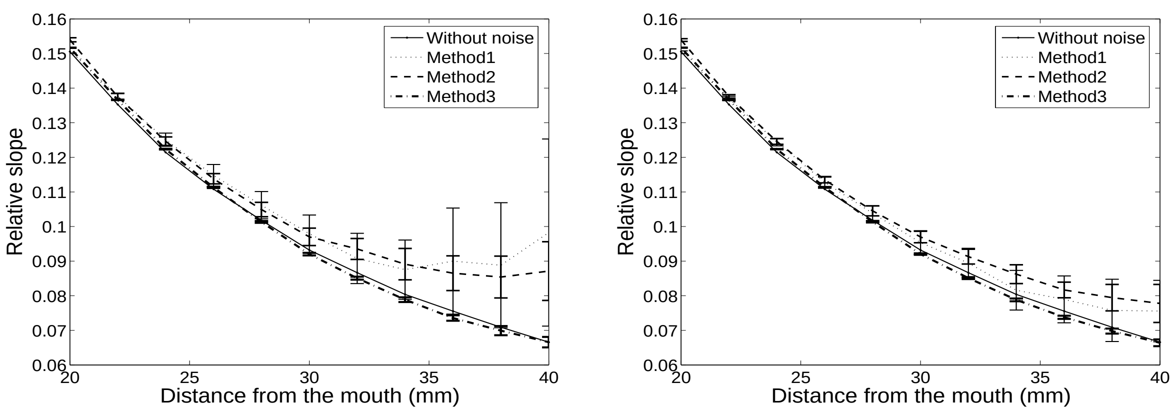
(a) (b)

Figure 8: Normalized denoised electric image using cross-correlated sum when there exist noise uniform noise from -5×10^{-6} to 5×10^{-6}; (a) lateral distance of a target object is $2cm$; (b) $4.8cm$ (solid : electric image without noise, dotted : distorted electric image, dashed : filtered image with cut-off frequency (a) and (b) 20% of the spatial sampling rate)



(a) (b)

Figure 9: Normalized denoised electric image using cross-correlation and a filtering when there exist uniform random noise with distribution range 30×10^{-6} and (a) lateral distance of a target object is $2cm$ (b) $4.8cm$ (solid : relative slope without noise, dotted : using low pass filter, dashed : cross-correlation, dashed dot : filtering after cross-correlation)



(a) (b)

Figure 10: Relative slope (a) uniform noise with range from -5×10^{-6} to 5×10^{-6} (b) Gaussian noise with variance 5×10^{-6} (solid : relative slope without noise, dotted : using low pass filter, dashed : cross-correlation, dashed dot : filtering after cross-correlation)

eters, maximal amplitude and maximal slope. The maximal amplitude can be estimated with the temporal cross-correlation result. However, the maximal slope is involved with the sensor readings along the rostrocaudal spatial axis. We apply a low pass filter over the electric image obtained from the cross-correlation method.

Fig. 9 shows a noise-free original electric image, and the denoised image by cross-correlation over temporal waveforms (method2) and by low pass filtering over the cross-correlation result along the rostrocaudal axis (method3).

	Amount	(1)	(2)	(3)	(4)	(5)	(6)
Method1	RMS	0.0177	0.0054	0.0014	0.0530	0.0047	0.0020
	STD	0.0091	0.0037	0.0009	0.0212	0.0032	0.0015
Method2	RMS	0.0130	0.0065	0.0027	0.0308	0.0045	0.0032
	STD	0.0038	0.0020	0.0004	0.0099	0.0014	0.0008
Method3	RMS	0.0015	0.0014	0.0014	0.0016	0.0014	0.0014
	STD	0.0007	0.0003	0.0001	0.0011	0.0002	0.0001

Table 1: Performance comparison of two method as a mean of error that is difference between relative slopes acquired from clean electric image and denoised image and a mean of standard deviation when the target object moves from $2.0cm$ to $5.0cm$ with interval $0.2cm$ and trial number is 100 (distribution range of uniform noise (1) 10×10^{-6} (2) 5×10^{-6} (3) 1×10^{-6} and variation of Gaussian noise (4) 5×10^{-6} (5) 1×10^{-6} (6) 5×10^{-7} (RMS: root mean square of difference, STD: standard deviation)

When the target object is at a far distance, the cross-correlation outputs over a set of electrosensors still show a rugged pattern of electric image along the spatial axis. The combination of the cross-correlation and low pass filter produces smooth electric image close to the original electric image. It indicates the two-phase filtering process can restore the original electric image from very noisy signals.

The method takes two steps in spatiotemporal dimensions. The electric image is first denoised in the temporal axis and then noise is removed along the spatial axis again. The two-phase filtering process in the spatiotemporal provides desirable slope information along the rostrocaudal axis, and we can extract most accurate relative slope.

Distance measure in noisy environment

From electric images, we can extract the relative slope and Fig. 10 shows the result. The relative slope is dependent on the lateral distance of a target object. The simulation with random noises is repeated fifty times and the performance has been measured. Fig. 10 (a) shows relative slope when the noise is distributed uniformly from -5×10^{-6} to 5×10^{-6} and Fig. 10 (b) shows the result with Gaussian noise whose variance is 5×10^{-6}. When the noise level decreases, we can acquire more similar curves to the relative slope curve in noise-free environment.

When we use low pass filtering after cross-correlation, we can acquire most similar relative slope to the relative slope obtained from noise-free electric signals. Table. 1 shows the performance comparison of three methods to remove noise when uniform and Gaussian noise are tested. The root mean squared error between noise-free relative slope and the filtered relative slope has been measured. We can easily see that the spatiotemporal filtering process greatly improves the performance.

Fig. 11 shows the relative slope changes for each filtering method. When the noise level increases from 1% to 20% of the maximal amplitude, only cross-correlation along the temporal axis, or only low pass filtering along the spatial axis is not much effective to obtain the desired relative slope.

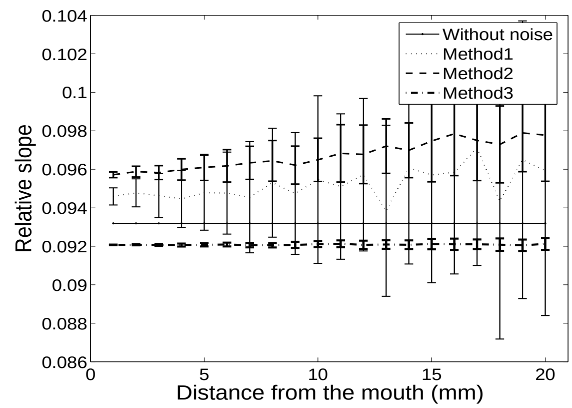


Figure 11: Relative slope when the noise level changes with a fixed target object (solid : relative slope without noise, dotted : using low pass filter, dashed : cross-correlation, dashed dot : filtering after cross-correlation)

It would be difficult to extract the accurate information of the object distance. We note that the cross-correlation can find the appropriate electric signals even for 40% of noise level signals. Weakly electric fish generate periodic EOD signals and we suggest that the self-generated electric signals help obtain the accurate information of distance of a target object in noisy environment.

Conclusion

Noisy signals are inevitable in the underwater environment. The electric signals generated by other underwater animals may be mixed up with the signals that the electric fish produces. In that environment, it is important to extract pure information of its own electric signal in the sensor readings.

An easy and simple method to remove noise in electric image is the filtering method. In this paper, it is shown that an electric image can be restored by low pass filter along the rostrocaudal axis when the noise level is small enough to remove. However, when the maximum amplitude of an electric signal decreases, the electric signal is distorted severely. The distance range in which the weakly electric fish can detect an object is very narrow, and it is known that weakly electric fish use the electrolocation based on distance (Nelson and MacIver, 2006; Babineau et al., 2007). Direct measurement of relative slope over raw electric signals can produce wrong estimation of the distance of a target object.

We use cross-correlation as an alternative method to obtain denoised electric image. Cross-correlation is generally used to measure the similarity of two signals. The cross-correlated sum becomes maximal when the frequency and phase of the two waveforms exactly matches. It is known that individual weakly electric fish discriminate electric signals that are characterized by species, sex, and another member of conspecifics (Kramer, 1994). If frequencies of EOD waveforms are different, then the cross-correlated sum has small value. Consequently, the cross-correlation has advantage to separate their own electric signals from another electric signals.

As shown in Fig. 10, we notice that the desired relative slope can be obtained when we take two steps for elimination of noise, cross-correlation and low pass filtering in spatiotemporal dimensions. The root mean square of difference and variance become much smaller even when a target object is far away from the weakly electric fish. The periodic efference copy signal used in the cross correlation is critical to remove a high level of noise. We suggest that the periodic waveform of EOD signals help localization of a target object such as prey or predator.

The electroreception of weakly electric fish can be applied to a robotic system to localize a target object in the underwater. The electric field can spread to every direction and it can be used to detect not only the location of a target object but also shape and size (Schwarz and von der Emde, 2001). These characteristics of the electroreception can be useful in the dark underwater environment. For the future work, we will test the electrolocation system with a robotic fish and show the possibility of application of electrosensors in the submarine system.

Acknowledgements

This work was supported by Mid-career Researcher Program through NRF grant funded by the MEST (No. 2010-0000460).

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