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Towards a Biorobotic Electrosensory System

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Abstract. Weakly electric fish hunt and navigate without visual cues by sensing perturbations of a self-generated electric field. The ability to detect, characterize and localize objects using electric fields is called electrolocation. This capability could be beneficial for underwater robots sent to explore dark aquatic environments, from those on Earth to those that might exist on other planets and moons such as Europa. Here we describe initial progress on the development of an artificial sensor array that could provide electrosensory capabilities to a submarine robotic explorer. The design of the sensor array and the associated signal processing algorithms are inspired by ongoing empirical and theoretical studies of signal detection, estimation, and active sensor positioning in weakly electric fish as they hunt for small prey. Here we describe a simple test setup consisting of a small electrosensory array and a robotic platform for controlling the movement of an electrolocation target. This system allows us to acquire and analyze electrosensory signals similar to those obtained a weakly electric fish.

Keywords: biorobotics, biomorphic, biomimetic, biosensor, computational neuroethology, electroreceptor, electrosensory, electrolocation

Weakly electric fish from South America and Africa have the ability to sense their environment using an active electric sense. These nocturnal fish hunt for prey and navigate through tropical rivers at night in turbid waters by emitting weak (millivolt-level) electric fields. Unlike strongly electric fish, the discharges of weakly electric fish are far too weak to stun prey or fend off predators. However, these weak electrical discharges allow the fish to perceive their surroundings in the dark using an electric sense (Bastian, 1994, 1995; Turner et al., 1999; Wickelgren, 1996).

In the neuroscience community weakly electric fish are a leading model system for investigating principles of active sensing. Wave-type weakly electric fish emit a continuous weak electric field around their body, called the electric organ discharge. Nearby objects that differ in conductivity from the surrounding water perturb the fish's self-generated electric field. Approximately 14,000 specialized electroreceptor organs embedded in the skin of the fish transduce these electric field perturbations. By processing data from the electroreceptor array, weakly electric fish can detect, localize, and discriminate objects in their environment. This ability is referred to as electrolocation. Because the strength of the electric field falls off steeply with distance (Rasnow, 1996), the electric sense is a short-range sense with an effective range that varies from a few centimeters for small prey to tens of centimeters for larger objects (MacIver et al., 2001).

By controlling the velocity and orientation of their bodies, and by adjusting the gain and filtering properties of neurons in the electrosensory processing pathways, these fish actively influence the strength and spatiotemporal pattern of the incoming electrosensory signals. Previous studies have shown that the weakly electric black ghost knifefish (*Apteronotus albifrons*) is able to detect small water fleas (*Daphnia magna*) at a distance of a few centimeters (MacIver et al., 2001). At this distance, the voltage perturbation at the skin is estimated to be on the order of 1 μV (Nelson and MacIver, 1999). This represents a change of approximately 0.1% in the RMS voltage level established by the electric organ discharge.

We are interested in understanding the behavioral strategies, neural mechanisms, and information processing principles that allow the animal to reliably detect, localize, and categorize objects in the environment based on these extremely weak sensory signals. In addition to providing biological insights, an understanding of the principles of electrolocation may find application in underwater robots. An electric sense could be a useful addition to the sensory capabilities to of an autonomous underwater robot sent to explore dark aquatic environments, from those on Earth to those that might exist on other planets and moons such as Europa.

To explore the feasibility of creating an artificial electrosensory system for underwater robots, we have developed a small active electrosensory array and a 3-axis robotic workcell for controlling the movement of a target object near the array. This prototype system allows us to acquire and analyze electrosensory signals that are similar to those experienced by weakly electric fish. In the future, we envision an expanded system of hundreds of sensors covering the surface of an autonomous underwater robot. Analyzing signal-to-noise characteristics and spatiotemporal image patterns collected from such a robot in a natural aquatic environment would greatly aid our understanding of the principles and mechanisms of electrosensory signal processing.

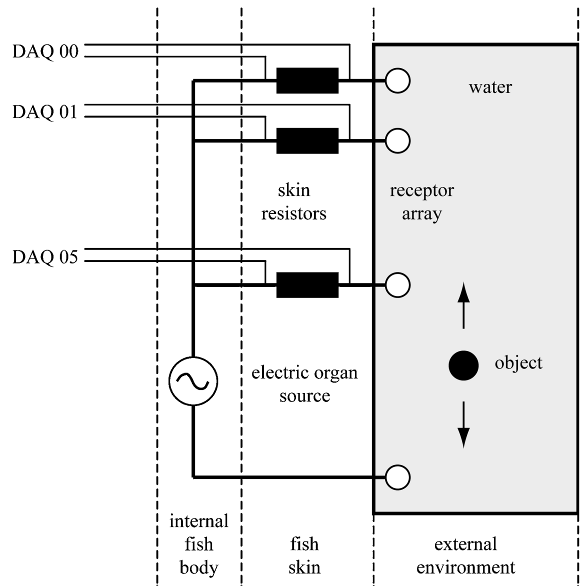

Figure 1. Schematic of the receptor array test setup. An electrolocation target was moved parallel to the submerged electrosensory array. Voltage signals, representing the transdermal potential experienced by each receptor, were recorded simultaneously from each channel as the target moved past the array.

Materials and Methods

As illustrated in Fig. 1, a linear electrosensory array was constructed using seven silver-silver chloride EKG electrodes (1 cm diameter) and spaced 1.5 cm apart. The array was mounted along the long side of a small water tank (25 × 14 × 10 cm) containing 100 μS/cm water (prepared as described in MacIver et al., 2001). One of the terminal EKG electrodes was used as a signal source to generate an oscillatory electric field representing the electric organ discharge (EOD). A 1 V (peak to peak) 1 kHz sine wave was applied across the signal source electrode to mimic the $\approx$1 kHz quasi-sinusoidal discharge of the weakly electric knifefish (Assad et al., 1999, Rasnow and Bower, 1996). A 10 kΩ series resistor was attached to each of the other EKG electrodes to represent the skin resistance of the fish (Fig. 1). The other end of each resistor was tied to a common voltage reference representing the internal body space of the fish. The voltage across each of the six skin resistors was continuously monitored by the data acquisition system. Signals were sampled at 1 kHz with 12 bit resolution using a data acquisition card (National Instruments Corp. DAQCard-AI-16E-4, Austin, TX, USA) and the MATLAB data acquisition toolbox (The MathWorks Inc., Natick, MA, USA) with a laptop PC (Inspiron 5000, Dell Computer Corp., Round Rock, TX, USA). Electrosensory targets (1 cm diameter metal and plastic spheres) were moved past the electrosensory array using a three-axis robotic workcell (RW-18B, Arrick Robotics, Hurst, Texas, USA). The position and velocity of the target object was controlled using custom motion control software.

Results

A preliminary assessment of system performance was made by qualitatively comparing the signals recorded from the array with empirical measurements of transdermal potential modulations recorded from weakly electric fish. Studies by Rasnow (1996) have shown that the electrosensory image of a small spherical object is spatially broad and weak for distant objects, and becomes sharper and stronger as the object approaches the fish. To examine whether our artificial active electrosensory system exhibited similar voltage patterns, a test object (a 1 cm diameter plastic sphere) was scanned parallel to the sensor array at four different distances from the array (6, 9, 12, and 15 mm) with a velocity of 4 cm/s. Distances were measured from the array to the center of the test object. As illustrated in Fig. 2, the signal profiles obtained from the artificial sensor array were qualitatively similar to those observed in electric fish. The voltage signal is strong and narrow when the object is close to the array, and becomes weaker and broader as the target distance is increased. Future studies will explore these relationships for the artificial array in more quantitative detail.

We have also begun to use the artificial electrosensory array to explore issues of neural information processing. Based on experimental studies of the response properties of electrosensory afferents (Xu et al., 1996; Nelson et al., 1997; Ratnam and Nelson, 2000), we have a good understanding of the relationship between the transdermal voltage and the change in firing activity of the afferent nerve fibers. Using a computational model of the combined receptor organ and afferent nerve fiber (Brandman and Nelson, submitted) we can predict the

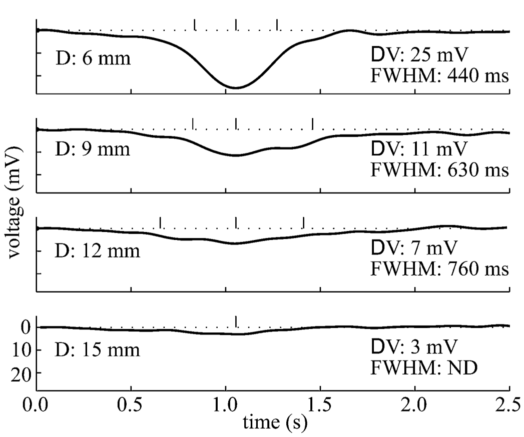

Figure 2. Voltage changes recorded from an individual array element as an object is scanned past the array at four different distances. The object was a 1 cm diameter plastic sphere. As the scan path was moved farther from the array, the peak amplitude of the perturbation decreased and the FWHM increased. The FWHM for the furthest scan was not determined (ND) because of the low signal amplitude.

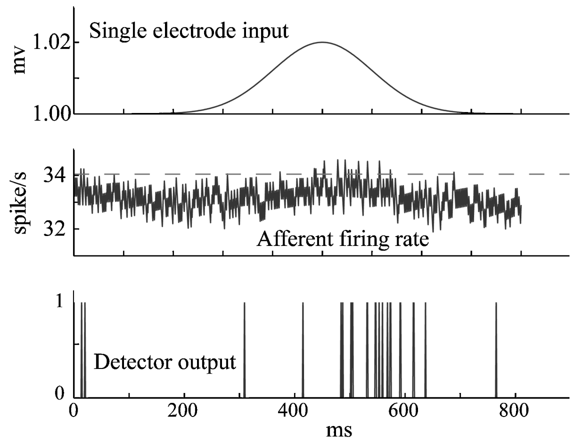

Figure 3. Illustration of a Gaussian voltage change similar to those measured being passed to a model of the electrosensory afferents. A neural detection algorithm based on a simple integrate-and-fire mechanism then processes the afferent signal.

changes in afferent spike activity arising from a change in transdermal voltage. As an illustration of this, Fig. 3 shows a sample of a Gaussian bump, similar in shape to those shown in Fig. 2 (but with sign flipped to simulate the effect of a conductive test object), along with the output of the afferent model. The afferent signal is subsequently processed by a biologically plausible detection algorithm to assess the detection efficiency and false alarm probability for detecting weak sensory signals.

Discussion

The artificial electrosensory array is still in the early stages of development. Initial results have been encouraging and demonstrate that object-induced voltage perturbations are qualitatively similar to those observed in electric fish. Numerous improvements in the array design and in the signal processing algorithms are planned for the future. Eventually, we envision embedding a 2D array of several hundred such receptor elements in the hull of a meter-long radio-controlled submarine. For example, about 400 receptor elements would be required to cover the surface of a 20 cm diameter, 1 m long cylinder using a grid spacing of 4 cm. Such a system would allow us to collect information regarding the signal-to-noise characteristics and spatiotemporal image properties of electrosensory scenes in natural aquatic environments. This platform would also provide a test bed for evaluating the real world performance of electrolocation algorithms, such as those for estimating target size, range and conductivity. We are also interested in using a mobile electrosensory array for investigating strategies for optimal sensory positioning during target acquisition. We have carried out detailed studies of how electric fish control the position of their sensory surface while hunting for prey in the dark (MacIver and Nelson, 2000; MacIver et al., 2001). These studies have provided us with precise information regarding the relative position between the prey and the sensor array prior to and following prey detection that we will compare to optimal strategies developed with the mobile array. Finally, a long-term goal is to develop control algorithms, inspired by the neural circuitry of weakly electric fish that would allow a robot to navigate autonomously in dark underwater environments using electrosensory capabilities.

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