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Electric sensing for underwater navigation

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1 Scope of chapter.

Underwater navigation in turbid water for exploration in catastrophic conditions or navigation in confined unstructured environments is still a challenge for robotics. In these conditions, neither vision nor sonar can be used. In the second case, echolocation has strong difficulties due to the signal scattering by particles along with the multiple interfering reflections by obstacles. Pursuing a bio-inspired approach in robotics, one can seek in nature which solution could be implemented to solve this difficult problem. In fact, several hundreds of fish species of Gymnotidae and Mormyridae families who have evolved on both African and South-American continents, have developed an original sense well adapted to this situation: the electric sense. In the mormyrid *Gnathonemus Petersii*, the fish first polarizes its body with respect to an electric organ discharge (EOD) located at the basis of its tail and generates in its near surrounding a dipolar electric field. Then, thanks to many transcutaneous electro-receptors distributed along its body, the fish "measures" the distortion of the electric field and infers an image of its surroundings. Known under the name of electrolocation, this omnidirectional active mode of perception is ideally adapted to the navigation in confined spaces bathed by turbid waters. Thus, understanding and implementing this bio-inspired sense on our technologies would offer the opportunity to enhance the navigation abilities of our under-water robots. In this chapter, we will report some designs and implementations of a new sensor inspired by electric fish on an underwater robot. In particular, we shall see how we can design a sensor inspired by the fish and how we can use it by taking inspiration of the electrolocation strategies discovered by the fish and studied by the biologists.

2 Biological principles.

In the 50's, researchers as (Lissmann and Machin 1958) have discovered that some fish living in fresh waters can sense electric fields around them. These fish have electro-receptive organs with which they can detect the very weak currents which exist in their natural surroundings. Named electrolocation, this sensorial ability can be classified into passive and active electrolocation. Sharks and rays use passive electrolocation in order to navigate in their surroundings and find their prey or to orient their body in telluric electric fields. These fish thus depend on exogenous fields that fortunately any animal produces with its muscular activity (Bullock and Heiligenberg 1986, Moller 1995). Unlike the passive electrolocators, the fish of Mormyridae and Gymnotidae families as well as the Apterionotes use active electrolocation to perceive their surroundings. In this case, these fish can measure the distortions of secondary electric fields reflected by the objects that they polarize by the emission of a primary field named basal field. Thanks to active electrolocation, these fish (see Figure 1(a)) can explore their environment, detects and analyzes objects or prey that do not produce any electric field (see Figure 1(b)) (von der Emde, Amey, Engelmann,

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Fetz, Folde, Hollmann, Metzen and Pusch 2008, Engelmann, Bacelo, Metzen, Pusch, Bouton, Migliaro, Caputi, Budelli, Grant and von der Emde 2008).

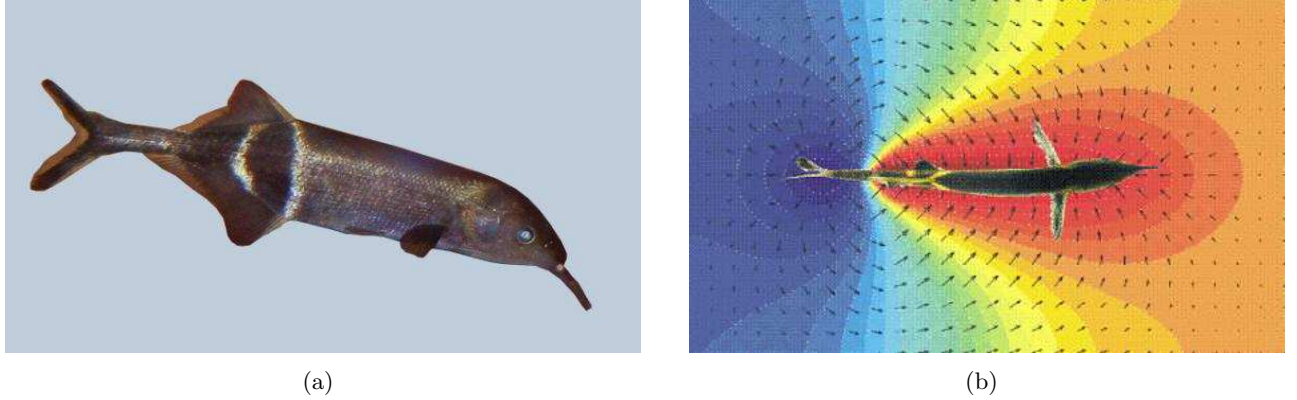


Figure 1: (a) The African Mormyrid fish *Gnathonemus petersii* or elephant fish. (b) Top view of the fish basal electric field.

Among the most efficient electric fish, the African fish *Gnathonemus Petersii* (voir Figure 1(a)) is probably the most extensively studied by biologists. As it is practiced by this fish, active electrolocation - which has a range of about the fish length - is based on the emission of an electric field in the close surrounding of the fish by polarization of an electric organ discharge (EOD) located in its tail with respect to the rest of its body. Once, this dipolar field emitted, the fish senses its perturbations by the objects through an array of electro-receptors distributed all over its skin (see Figure 1(b)). Based on this property, Brian Rasnow in 1996 (Rasnow 1996) brought the first relations between some aspects of the environment and the electric intensity distribution on the skin of the fish, that we call the electric image. He established a model that he derived from simple electromagnetism conditions to study the effect of the distance and the dimension of a sphere placed in the vicinity of the fish. His simple model helped him to show the relation between the shape of the electric image and the distance and dimensions of the spheres. Though it is applicable with restrictive conditions the model of Rasnow helped the robotic community to start the project of building a bio-inspired electric fish robot.

3 Biomimetic systems.

Based on this principle, several designs of electric sensors were proposed (Solberg, Lynch and MacIver 2008, Mayton, LeGrand and Smith 2010, Bouvier, Boyer, Girin, Gossiaux, Lebastard and Servagent 2013, Servagent, Jawad, Bouvier, Boyer, Girin, Gomez, Lebastard and Gossiaux 2013). In their principle, all designs consist of a set of conducting electrodes displayed on the boundaries of the insulating shell of a sensor or a robot. These electrodes are electrically connected between them by a circuit embarked within the sensor and such that once polarized by a voltage (or current generator) these electrodes produce, by virtue of the Coulomb's law a loop of currents in the conductive surrounding of the sensor. This loop emanates from the emitting electrodes (play the role of EOD) to meet the receiving electrodes and is closed by the internal circuit of the sensor which measures the electric variables perturbed on the receivers. Till to date, there exist two great types of technologies inspired of active electrolocation. The first one is named U-U (Solberg et al. 2008, Bouvier et al. 2013), consists in generating an electric field (basal field) by imposing a voltage (U) between the emitters and the receivers (see Figure 2), and in measuring the perturbed voltages induced by the surroundings (U) on the receivers. The second, named U-I (Bouvier et al. 2013, Servagent et al. 2013) produces its basal field in the same manner (U). However, the measures of the perturbations produced by the objects on the receivers are currents (I). Remarkably, the U-I technology allowed one to obtain the range of the most efficient fish (the elephant fish previously

evoked) while the range of U-U sensors does not exceed 1/3 of the total length of the fish. This feature is probably one of the successes of the birth of the first autonomous robot navigating with electric sense (Demonstrations of the Angels platform 2013). Beyond active electrolocation, other measurement modes have also developed allowing to achieve passive measurements and which are consequently named 0-U and 0-I, the first letter indicating here no-emission, the second being related to the measurement (Bouvier et al. 2013, Servagent et al. 2013).

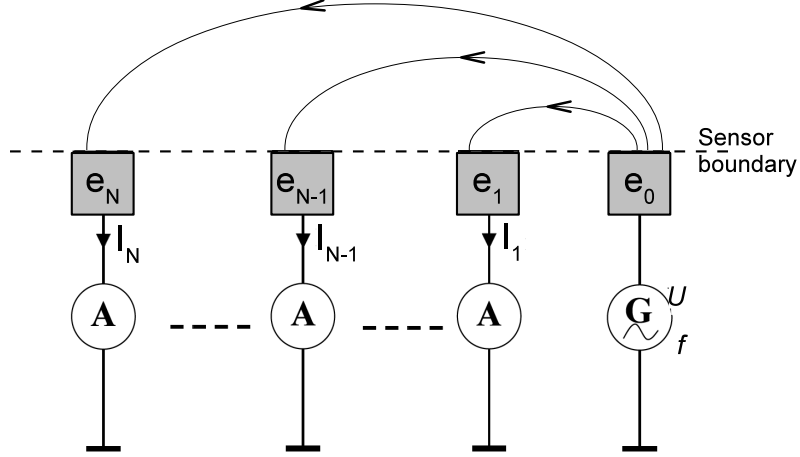


Figure 2: Principle of the $U - I$ measurement mode for a probe with an arbitrary number of receptor electrodes. The electrode e_0 (emitter) is polarized with respect to the others (receivers) e_1 to e_N .

These different realizations have given birth to several more fundamental results in particular in terms of modeling, perception, reconstruction of the environment and navigation control. In the field of modeling, a novel approach has been developed. In its principle, the approach aims at replacing the simultaneous electric interactions between objects and the sensor by an expansion of successive reflections travelling between ones and others (Boyer, Gossiaux, Jawad, Lebastard and M.Porez. 2012). Remarkably, the approach allows one to obtain very concise analytic models. Moreover, it gives access to an intuitive hierarchy of electric interactions in complex scenes (several objects and sensors). Furthermore, it allows one to manage the order of approximation of the resulting model which can be compared with reference numerical codes as those based on the Boundary Elements Methods (Liu 2009, Porez, Lebastard, Ijspeert and Boyer 2011).

In the continuity of these results on modeling, other works were pursued in the field of perception and control. In particular, a classical approach based on the use of a model integrated in a Kalman filter has been applied with some success to the problem of navigation in a tank. The approach is based on the reconstruction of the environment where the objects are modeled by spherical primitives (Lebastard, Chevallereau, Girin, N, Gossiaux and Boyer 2013). They show the efficiency of the approach especially for the 3D localization of small objects. Let us remark that other approaches respectively based on the particle filter (Solberg et al. 2008) and Bayesian filters (Silverman, Snyder, Bai and MacIver 2012) have also been proposed.

More recently, it has discovered that it was possible to address the problem of navigation in encumbered environments without reconstructing it, i.e. without using any model. The approach is based on the bio-inspiration and the concept of embodiment. More precisely, by exploiting the morphology of the sensors (slender shape, bi-lateral symmetry), it is possible to address the problem of navigation as that of the interaction of the sensor's body with its electric field distorted by its physical environment. In this context, a set of reactive control laws have proposed, its principle is based on the alignment of the body of the robot-sensor on the electric lines emitted by the polarized object. Remarkably, these strategies in fish has recovered, the fish hunt by following the electric lines that lead them to their prey.

Once implemented and tested on experimental tests, these bio-inspired (and embodied) strategies allow avoiding the use of any model, while giving relevant and robust behaviors to the sensor (robot) (see Figure 3). Among these behaviors, we find "obstacle avoidance" or the active seeking of conducting objects (see Figure 3) (Lebastard, Boyer, Chevallereau and Servagent 2012, Boyer and Lebastard 2012). Furthermore, the approach is a very nice example of the concept of morphological computation in the meaning of embodied intelligence (Pfeifer, Lungarella and Lida 2007).

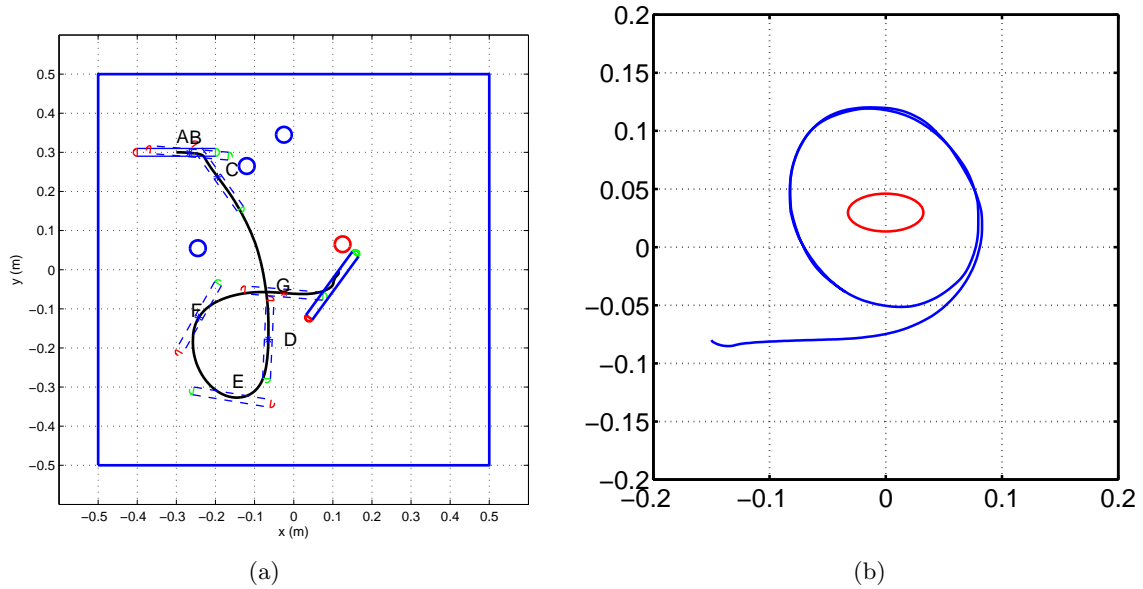


Figure 3: Application of a reactive control law on a slender probe : (a) (Insulating) obstacle avoidance and conductive object seeking. (b) exploration of the shape of an object by revolving around it.

Based on this fundamental and experimental framework, the ANGELS project has proposed the first autonomous underwater robot equipped with electric sense using the reactive control approach previously evoked, the experiments (Demonstrations of the Angels platform 2013) have shown the feasibility of exploiting the electric sense in under-water robotics in constrained environments (encumbered of many obstacles, turbid water...).

4 Future directions.

Beside the impacts brought by the electric sense in itself, initiated a new generation of autonomous modular and reconfigurable underwater robots devoted to the agile swimming in confined environment immersed by fluids which can be sufficiently dirty and encumbered to prevent the use of vision and sonar. The concept of adaptive morphology to a kind of electric body which self-adapts to environment, and which once combined to the mechanical possibilities and modularity, greatly multiplies the possibilities of adaptation (up to the most complex ones involved by sociologic interactions between small autonomous sub-agents sharing a same collective electric field as this of a single entity). By its high adaptability, a new underwater robot generation, which could be used for a number of different robotic applications. In particular, on the long term, modular robots with electric sense could be of use as assistants for service professionals (underwater and pipes inspection for offshore platforms and industries, sewage networks...) and agents for security (exploration of unknown or hostile environments). It could also be used in environments submitted to very sever conditions for autonomous robotics as the exploration of abyss. Several industrials have a strong interest for the technologies. They can be essentially classified in two sets: that of factories involved in water treatments, and a second set more involved in nuclear energy. Let

us note on this point that electric sense seems having a strong potential for the exploration of immersed pools with dirty waters contaminated by radioactivity. In this case, factories are interested in shape recognition, mapping. Going further, in the perspective of generalizing electric sense to the air, we could then imagine equipping our future robots of a kind of electric body interacting with their environment with simple reactive strategies. In particular, electric sense has the very interesting ability to distinguish living from dead objects, a feature highly relevant for man-robot cooperation.

5 Learning more.

For the reader wishing to learn more, on biologist principles and experimentations (Bullock and Heiligenberg 1986, Moller 1995, Caputi, Budelli and Bell 1998, Hopkins 2009, von der Emde et al. 2008, Engelmann et al. 2008, Pereira, Aguilera and Caputi 2012). A new approach of the modeling has been developed in (Boyer et al. 2012) and this approach allow a concise analytic models of the environment of the sensor. The classical control approach based on the reconstruction of the environment based on the use of a model integrated in a Kalman filter (Lebastard et al. 2013), in a particle filter (Solberg et al. 2008) and in a Bayesian filters (Silverman et al. 2012) have been applied with some success to the problem of reconstruction of environment and navigation. A more recent control based on the concept of morphological computation in the meaning of embodied intelligence in developed in (Lebastard et al. 2012, Boyer and Lebastard 2012).

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