Underwater robots equipped with artificial electric sense for the exploration of unconventional aquatic niches

Stéphane Bazeille, Vincent Lebastard, Frédéric Boyer

Abstract This article presents different use of the electric field perception in the context of underwater robot navigation. To illustrate the developed navigation behaviours we will introduce a recently launched european project named subCULTron and will show some simulation and experimentation results. The project subCULTron aims at achieving long-term collective robot exploration and monitoring of underwater environments. The demonstration will take place in the lagoon of Venice, a large shallow embayment composed of salt turbib water that represents a challenging environment for underwater robots as common sensor like vision or acoustic are difficult to handle. To overcome turbidity and confinement problems our robots will be equipped with artificial electric sensors that will be used as the main sensorial modality for navigation. Electric sense is a bio-inspired sense that has been developed by several species of fish living in turbib and confined underwater environment. In this paper, many different robotic behaviours based on the electric field perception will be presented, in particular we will address reactive navigation, object/robots detection, and object localization and estimation.

Keywords: Underwater robots, electric sense, autonomous navigation, environment monitoring.

Dr. Stéphane Bazeille
Laboratoire des Sciences du Numérique de Nantes (LS2N), Institut Mines Télecom Atlantique, France, Contact: e-mail: `stephane.bazeille@gmail.com`

Dr. Vincent Lebastard
Laboratoire des Sciences du Numérique de Nantes (LS2N), Institut Mines Télecom Atlantique, France,

Pr. Frédéric Boyer
Laboratoire des Sciences du Numérique de Nantes (LS2N), Institut Mines Télecom Atlantique, France,

1 The subCULTron project

1.1 Working context

Water covers roughly 70% of the planet but is still mainly unknown due to its difficult exploration by humans (vast size, changing light conditions, turbidity). However, the underwater habitats has a high-impact for climate and ecological balance and requires the development of new technologies for robots. Within the subCULTron project we aim at developing new robotic technologies for the collective exploration and the monitoring of underwater environments. SubCULtron (SUBmarine Cultures perform Long-Term Robotic Exploration of unconventional environmental Niches) is a project supported by European Union Horizon 2020 research and innovation program [1]. Its application will be focused on collecting large and long term environmental data (for instance: pressure, temperature, pH, salinity, conductivity, turbidity, chemical composition of water, water level, flow rate and pictures about the marine fauna and flora). These information will be in turn studied by biologists to understand the changes inherent to human activities in the region of Venice. The project is coordinated by the Artificial Life Lab of the University of Graz (Austria) and includes the Unit of Social Ecology of Université Libre de Bruxelles (Belgium), Cybertronica Research Center of Advanced Robotics and Environmental Science (Germany). The Laboratoire des Sciences du Numérique de Nantes (France), the Biorobotics Institute at Scuola Superiore Sant Anna (Italy), the Faculty of Electrical Engineering and Computing at University of Zagreb (Croatia), the Consortium for coordination of research activities concerning the Venice lagoon system (Italy).

1.2 Swarm exploration and monitoring

The novelty of subCULTron concentrates on the data collection that will be performed by a large robot swarm constituted of more than 130 entities (a swarm is a group or aggregation of free-swimming organisms). This artificial robot organization will be composed of 3 classes of cooperating robots (see figure 1): 5 floating platforms called artificial lily pads (aPad), 100 artificial mussels (aMussel) and 30 artificial fish (aFish) that will collaborate together to perform their mission.

aPad: The aPads are floating robots (see figure 2, 3.b). This class of autonomous robots globally localized by GPS and equipped with solar panels will be used as geolocalization satellites and recharge/gathering station for the underwater robots. They will communicate with the underwater robots though acoustic sensing. aPads will also maneuver actively and they have the longest runtime.

[1] subCULTron (2015-2019), EU-H2020, FET PROACT-2-2014 under grant agreement no 640967. http://www.subcultron.eu

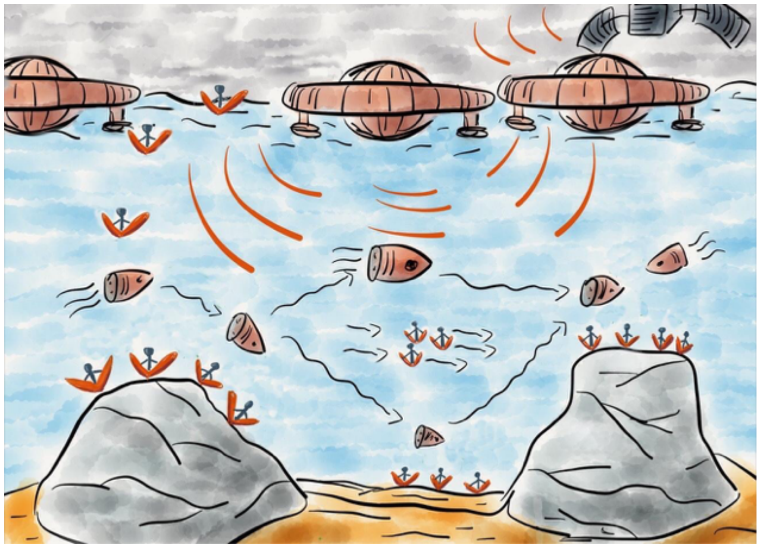

Fig. 1 Illustration of an experiment using the 3 different robots developed within the subCULTron project.

aMussel: The aMussels is a class of underwater robots that sits on the ground (see figure 3.a and 3.b). These robots have an actuation limited to a buoyancy device. They will dive, and autonomously surface for recharge. They will be used under a low-energy consumption regime and they will harvest energy from the bacteria. These robots will self-distribute in the habitat, and then be used as landmark, and data storage station for aFish.

aFish: The aFish are the most active robots (see figure 4). aFish will browses the habitat and organize to explore an area and collect data. As the most active robot, they have to autonomously manage their energy and to recharge their battery on aPads when they need. They will communicate with aMussels and aPads to localize and will exploit information collected by other aFish in order to actively explore the environment.

All experiments will take place in Italy in the Venice Lagoon (a shallow water area of 500 km^2). This place is a particularly challenging environment for common underwater robots as it is a large heterogeneous area constituted of: a network of turbulent canals, open waters, mud flats, tidal shallows or salt marshes. It presents many difficulties that have not been addressed: a ubiquitous turbidity, a fluctuating salinity, potential strong water currents and a large variability of biological activities. As common sensing cannot be used under these conditions, its exploration pushed us towards the use of a new perception sensor: the electric sense.

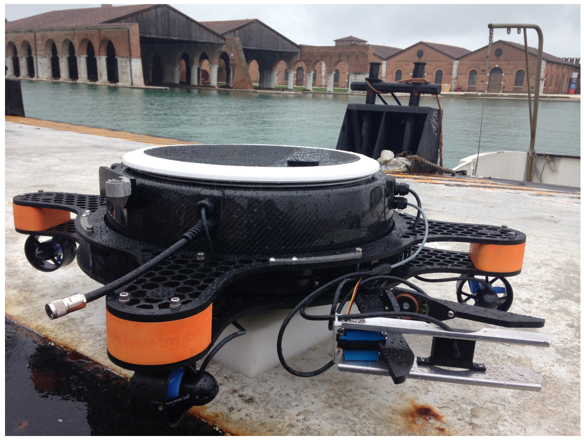

Fig. 2 An aPad in the Arsenale in Venice.

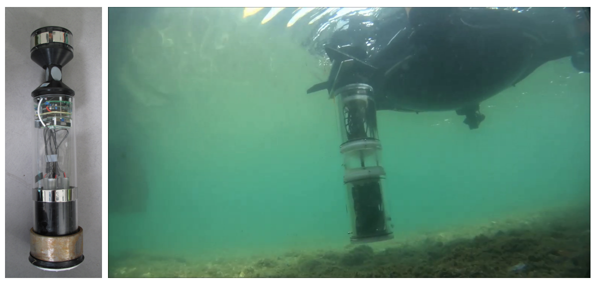

Fig. 3 Left: An aMussel, Right: An aMussel recharging on an aPad.

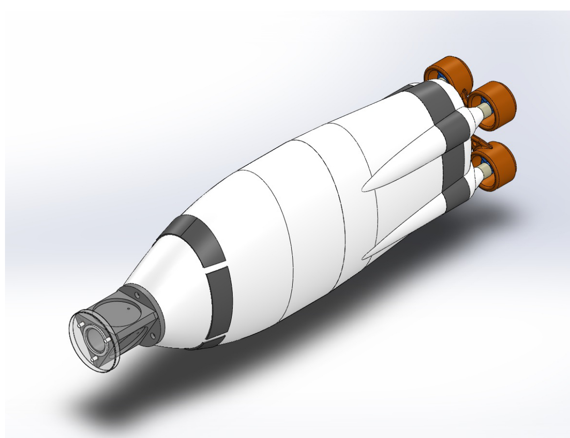

Fig. 4 First design of the aFish (artificial fish).

1.3 Robots sensors equipment

In the following we will concentrate our discussion on the underwater robots: the aFish and the aMussel. The aPad as a floating platform will not be equipped with electric sense. The underwater robots will dispose of 2 different set of sensor. A set of sensors to collect data about the environment (turbidity, pH, temperature ...) and navigation sensors. Among these navigation sensors, robots will dispose of common underwater sensors: an imu, an acoustic pinger and receiver, a camera, and a modulated light perception system. Besides this sensors underwater robots will include an artificial electric sensor that will be used as their main perception and communication sensor. Few reasons can explain this choice of electric sensing. First the omnipresence of suspended matters makes the water turbid or muddy, and the shallow waters rich in vegetation makes the environment cluttered and confined. These two specificities prevent robots from using common long and medium range underwater sensors such as sonar and vision. Vision, because the visibility is dependent on the available light energy which dramatically decreases in highly turbid turbulent and polluted waters. Sonar, because the reverberation of multiple echoes from the obstacles and the diffraction by suspended particles jam the sonar signals and makes their interpretation difficult. The electric sense giving an omnidirectional perception of the environment robust to the lack of light and the turbidity makes it perfectly suitable for our applications.

2 The electric sense in nature

Electric sense has been observed almost exclusively in aquatic or amphibious animals, the known exceptions being echidnas, cockroaches and bees [8]. Underwater, several species of fish have the capacity to sense changes in electric fields in their vicinity [6]. Among fishes, we can distinguish two typical modes of electroreception: some fish passively sense changes in the nearby electric fields (passive electric sense) [10], some generate their own weak electric fields and sense the distortions of these fields with their skins (active electric sense) [7][15].

2.1 Passive mode

Passive electroreception is the most common modality: the fish senses the weak electric field generated by other animals (prey or conspecifics) and uses it to locate them. These electric fields are typically generated by nearly any species due to the activity of their nerves and muscles. Passive electric sense is used by several species of sharks and rays that have evolved specific electro-receptors named Lorenzini ampullae [10]. It has to be noted that these receptors are so sensitive that these fish also use them to orientate along the telluric fields or to sense the weak gradients of salinity. When hunting, the range of perception of passive electroreception is generally around few meters.

2.2 Active mode

In active electric sense, the fish called weakly electric fish, can sense their nearby environment by detecting the distortions of a self generated electric field. This electric field is generated thanks to an electric organ that is located at the base of its tail. It generates a dipolar shaped electric field around the fish which is the distorted by the nearby objects as it shown on figure 6. Then the distortions is measured using a dense array of electro-receptors distributed over the fish skin. This phenomena called "electrolocation" can be compared to the echolocation used by dolphins, where the carrier is no longer an acoustic wave but an electric field. Because electric emitters are dipoles instead of sources, electric sense has a much shorter range (around 1 body length) but it has the advantage to be omnidirectional. They can also use electric sense for passive sensing to hunt their preys or to escape from their predators. Most of electric fish are principally nocturnal and live in confined turbid waters of the equatorial forests [14], that is to say waters that are rich in suspended particles with many obstacles such as the roots of the trees. Beyond perception, active electric fish can also communicate by modulating their electrical activity and they use this further ability for courtship behaviors or to mark out their territory. As an example, figure 5 shows the elephant-nose fish, the most clever electric fish. Recent behavioral experiments have shown that through active electric sense, this fish can localize preys, predators, conspecifics and also inert objects when they are electrically contrasted with respect to the water. Moreover, researchers showed that the fish can also identify the electric nature (conductive, insulating), and discriminate the sizes and shapes of objects [18]. Its polarization is performed in short pulses. Other fish of the family of *Gymnotide* use the same principle of reception but with a sinusoidal (alternative) electric field. These fish are named wave fish and their emission mode has inspired the artificial electric sensors [16].

Fig. 5 A weakly electric fish: Gnathonemus petersii.

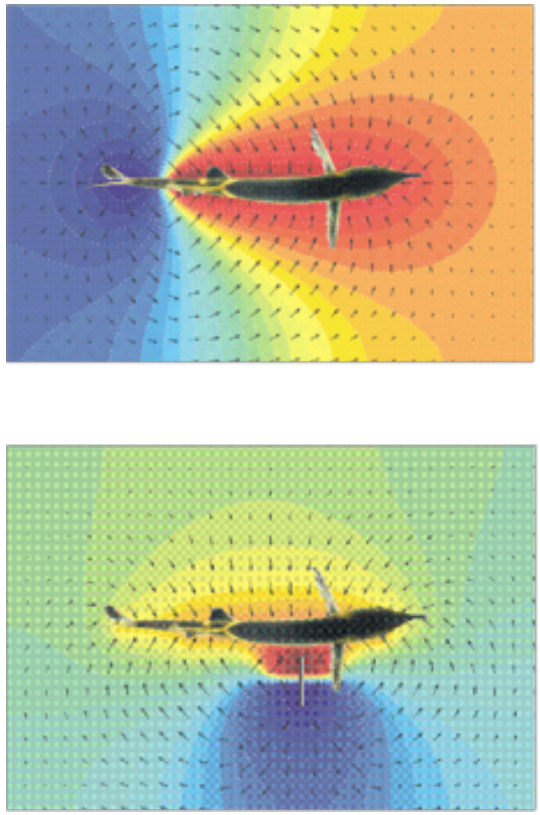

Fig. 6 Up. Basal electric field produced by the weakly electric fish. Down) Electric field re-emitted by the conductive polarized cylinder situation on the right side of the fish.

3 Artificial electric sense

3.1 Use of artificial electric sense for AUV

Electric sense is a short range omnidirectional perceptual ability well suited for confined environments and turbid or muddy waters. It is cheap, easy to integrate on a robot and can be used in different context such as reactive navigation, docking, obstacle avoidance and object recognition. Both active and passive modalities (active or passive) can be used depending on the application as the weakly electric fish do. When speaking about reactive navigation, a first example that clearly illustrates the advantage of the electric sense is the underwater docking of a passive robot on an active station for battery recharging or data exchange. Another possible use of the reactive navigation in the context of an active robot is to react to the electric field lines reflected by the nearby polarized objects to perform basic behaviors as obstacle avoidance or object seeking. Beyond these reflex behaviors, electric sense can be fused with other sensing modalities, as for instance inertial measurements to perform more complex cognitive tasks as shape recognition [11] or mapping the environment while self-localizing, a topic never addressed in the artificial electric sense community. Disadvantages of electric sense is the short range and the electric measures potentially difficult to interpret when the environment is complex (more than one emitting agent, many objects for example). For these reasons, it has to be complemented with other sensors.

3.2 Electric sense in subCULTron

As discussed previously, electric sense being a short range sense, it will be supported with hydro-acoustic for long range localization, and complemented by modulated light at short range. Redundancy at short distance sensing has been chosen make the system more robust. Modulated light is an active sense as well. It is based on the emission of light that is reflected back by the obstacles and detected by some photoreceptors. Though being not much affected by the turbidity of the water, it can be severely disturbed by external light sources such as the sun when it is used close to the surface. In clear water, it has a little longer range than electric sense, typically about 1 meter but each photoreceptor has a small cone of perception then many devices are needed to obtain an omnidirectional perception without blind spots. Finally, 2 additional sensors will equip our underwater robots: an Inertial Measurement Unit (IMU) that gives the robot linear velocities and angular rates, and a pressure sensor that gives the depth. These proprioceptive information will be used for robot balancing (pitch, roll), control of the navigation (heading, velocity, depth). About electric sense, the two modalities will be used depending on the behaviours we need. Active mode will be extensively used to perceive the environment and navigate autonomously while avoiding obstacles. Passive mode will be used to navigate towards active robots (reach a base or follow a conspecific). In the following, we will consider passive electric sense as a particular case of active electric sense in which the electric field is no longer generated by the same sensor but by an external active dipole that can be another robot or a docking station for example. Passive electric sense will also be used as a way of communication between robots. However, the word communication will not refer to an exchange of an explicit information through coded messages, but will rather inform about the presence and position of others robots.

3.3 Basic principle

Two artificial electric sensing technologies inspired by electric fish exist today $U-U$ [2] or $U-I$ [3][17]. The first letter designates the first electric input controlling the electric emission (here a voltage U), the second, the measurement variable (I denotes a current). In both cases, the sensor is an insulating axisymmetric (plastic) shell on which a set of conductive electrodes are arrayed. The electric field is generated by setting a voltage on at least two electrodes in contact with the water. Though, both techniques ($U-U$ and $U-I$) share this common emission principle, in the $U-U$ mode, the other electrodes are paired floating potential electrodes between which the voltage is measured. While in the $U-I$ mode all of the electrodes except the emitter are grounded, and the currents that flow across each of them are measured. It is worth noting here, that till today artificial electric sense still remains restricted to tap waters and electric sensors designs were built for planar navigation. The sensor [17] will be used for some experiments presented in Section 5 is presented on figure 7. It is composed of an insulating shell with a set of 4 macro-electrodes denoted ε_i, $i=0,1,2,3$. The shell and the array of electrodes obey to a bilateral (left-right) symmetry. The back macro-electrode, ε_0 stands for the emitter, while the others $\varepsilon_1,\varepsilon_2,\varepsilon_3$ are the receivers. The emitter ε_0 is set under a controlled voltage U with respect to all the receivers which are grounded. This voltage U is imposed through a sine wave generator. Note here that a continuous voltage would generate an undesirable electrolysis. The surrounding water being a conductive medium, such a polarization of the sensor generates an electric field in the sensor surrounding (see figure 6). When there is no object within the robot's range, this electric field is named "the basal field".

All macro-electrodes are divided into 2 electrodes as shown on figure 7. The basal currents measurements are gathered in the vector $I^0=[I_1,I_2,I_3,I_4,I_5,I_6,I_7,I_8]$. These currents are entirely modeled by the following the vector-equation:

$$I^{(0)}=C^{(0)}\overline{U}, \tag{1}$$

where $C^{(0)}$ is a 8×8 vector modeling the basal conductivity (indexed (0)) of the current paths between the emitter and the receivers, and $\overline{U}$ a vector of size 8×1 in which values are set to zero for the receiving electrodes and to U for the emitting ones. The currents measurement vector include 8 measurements, but it has to be noted that only 6 are useful because on the real robot due to an hardware limitation the current cannot be measured on the emitting electrodes. The currents vector only depends on the sensor's geometry and the medium's conductivity γ_0 through the relation:

$$C^{(0)}=\gamma_0 S^{(0)}, \tag{2}$$

where $S^{(0)}$ is a matrix modeling the influence of the shape of the sensor on the conductance between the emitter and the receivers. For example, designing a sensor shape more and more complex, makes $S^{(0)}$ and so $C^{(0)}$ decrease since it obliges the electric current lines to be more and more curved. Another degree of freedom encoded into $S^{(0)}$ consists of the geometry of electrodes whose decreasing the size, makes $C^{(0)}$ decrease. Note also that $C^{(0)}$ can be obtained once for all either by numerical computation or in situ, through a preliminary calibration phase. Then, when an object (obstacle, other robot) appears in the sensor's surrounding, the vector of measured currents I becomes:

$$I = I^{(0)} + \delta I = (C^{(0)} + \delta C)U = CU, \tag{3}$$

where δI represents the perturbative component of the measured currents which images the presence of the object, and δC is its contribution to the external conductivity between the emitter and the receivers noted C. This perturbative conductivity δC depends on the geometry of the object, its position, as well as the dimension-less number $\lambda = \gamma/\gamma_o$, named contrast coefficient. In this respect note that when $\lambda = 1$, $\delta C = 0$, and the object is electrically transparent.

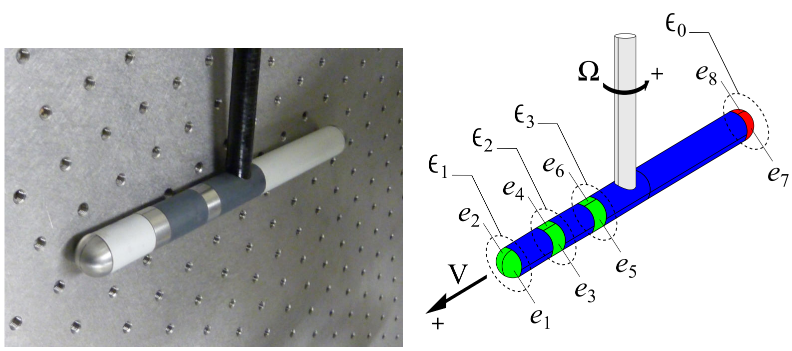

Fig. 7 Left: Artificial electric sensor [17], Right: Design of the sensor with our notations.

4 Electric sense for the subCULTron

4.1 Electric sensing in salt water

One of the main difficulty of the project is that we have to work in sea waters i.e. salt water, that is too say a water with a conductivity 100 higher than tap water. The conductivity defined as a measure of the capability of a medium to pass electric flow, depends on many parameters in particular the chemical compounds of water. Salinity has the strongest influence, the temperature has also a non negligible influence. As an example, tap water has a conductivity that ranges in $[0.005 - 0.05]$ S/m and salt water ranges in $[1 - 10]$ S/m. The conductivity in the lagoon of Venice is highly varying temporally and spatially, it has been estimated in [2-7] based on data collected in the lagoon in 2015. For our robots we preferred to use the U-I mode as it has a greater range equivalent to the fish range and it is more adapted to a use in sea water. Through this implementation we consider that the electromagnetic waves in the water are in the range of electric field frequencies ($\frac{w}{2\pi} < 50kHz$), and we restrict electric sense to a measure of the amplitude of electric current, the phase is neglected. As the conductivity is large and varying, the hardware presented in [17] has been augmented with a micro-controller to maintain a suitable emission with respect to the conductivity changes. When the conductivity increases the sensor saturates so the voltage U of the emitter has to be decreased, on the contrary when the conductivity decreases the amplitude has to be increased in order to keep the signal noise ratio and the perception range.

4.2 The importance of the sensor morphology

For our 2 underwater robot, the morphology of the sensor has been also optimized in order to maximize the sensor range and maximize the information obtained from the current measures and ease the robot control. To maximize the sensor range we increased at the maximum the distance between the receivers and the emitters. On both robot the emitter and receivers are on opposite sides of the robots. Regarding the receiving electrodes we respected also a symmetric positioning constraint: aMussels are axisymmetric and aFish will have a left-right and up/down symmetry. Finally again to enhance the perception, the number of electrodes was chosen depending on the behaviours of each robot. For the aMussel which are vertically put on the seabed, we chosen to place the ring emitter at the bottom and 4 quarter of circle electrodes on the top as receivers to obtain directionality component from the current measures (see figure 8). For the aFish, we planned to have on a ring shape emitter on the tail and four electrodes on the nose (see figure 4). These receivers will be positioned in order to allow the detection of obstacles around the robot in 3D.

5 Experiments results based on electric sense

For all the experiments described in this section we consider the aMussel is a cylinder with a length $l_M = 50cm$ and a diameter $r_M = 12cm$ (see figure 8). Regarding the aFish, that has still not be produced we used the slender probe [3] presented on figure 7. It has a length $l_F = 20cm$, a diameter of $r_F = 2cm$. We will show 4 different use of electric sense illustrated using the subCULTron underwater robots. Among the experiments shown, the aMussels experiment have been done in salt water, all other experiments have been only performed in tap water.

5.1 Localizing an active robot from a passive robot

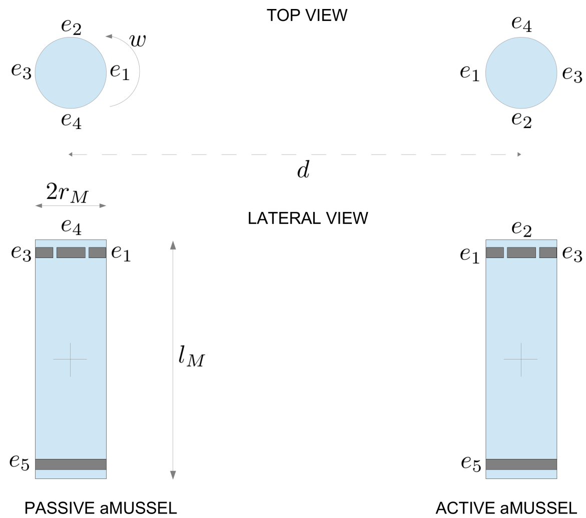

Fig. 8 aMussel experiment set up.

In this first experiment, we consider a passive robot and an active robot in its range of perception in salt water. Our goal is to estimate the direction and the distance of the active robot (emitting an electric field) from the passive one. We only dispose of the 4 measured currents on the passive robot that linearly depends on both the conductivity γ_0, and the imposed voltage U. These two quantities are supposed unknown. To infer the distance and directionality, we computed the 2 following currents ratio from the 4 raw currents I_i (i=1,2,3,4) measured on the 4 electrodes e_1, e_2, e_3, e_4 (see figure 8):

$$R_{1,3} = \frac{I_1}{I_3} - 1, \qquad R_{2,4} = \frac{I_2}{I_4} - 1 \tag{4}$$

It has to be noted that computing the currents ratio makes our measurement independent from the conductivity. From these ratio we can estimate the directionality φ of the active robot defined by:

$$\varphi = ATAN2(R_{2,4}, R_{1,3}) \tag{5}$$

where φ is an angle that is defined a fixed reference frame attached to the passive robot. The direction estimated, we obtain the distance d using the following function:

$$d = 0.2\sqrt{(\ln R_{2,4})^2 + (\ln R_{1,3})^2} \tag{6}$$

This function is a parametrical model of the currents that has been computed in a preliminary phase from different measurements of the 2 currents ratio at different distances. As the currents ratio does not depend on the conductivity but only on the morphology of the aMussels and the distance between the 2 robots the calibration can be done once for all in any water medium. To illustrate this localization of an active robot from a passive one in salt water we present on figure 9 the raw currents measured on the passive robot while rotating it in place (changing w on figure 8). It can be see that as w changes the maximum current value changes from electrodes 1 to 4. It is maximum when an electrode of the passive robot is facing the active robot. On figure 10, we show the currents measured on the passive robot as we pull it away from the active one but keeping the orientation fixed. The currents are in this case decreasing as the distance increases. It can be seen the perception range of the sensor is about $0.8m$. To summarize, by using such a method we can estimate the robot distance and direction of an active robot from a passive one just by measuring 4 currents and without the knowledge on the conductivity or the voltage U.

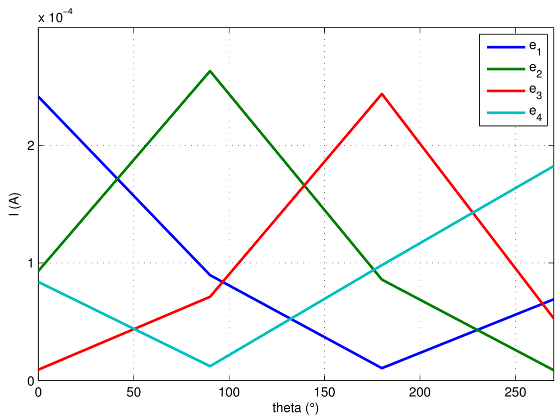

Fig. 9 Raw currents measured on the 4 electrodes of the passive aMussel with 4 different orientations $(0°, 90°, 180°, 270°)$ at the same position.

5.2 Reactive navigation using active electric sense (memoryless)

In this simulated experiment we suppose that we use the robot presented on figure 7. The macro-electrode ε_0 is set to a potential U supposed known. On each of these receiving electrodes the current is measured and we obtained the following measures: $I_1, I_2, I_3, I_4, I_5, I_6$. These values can be re-parameterized by the following 6 scalars:

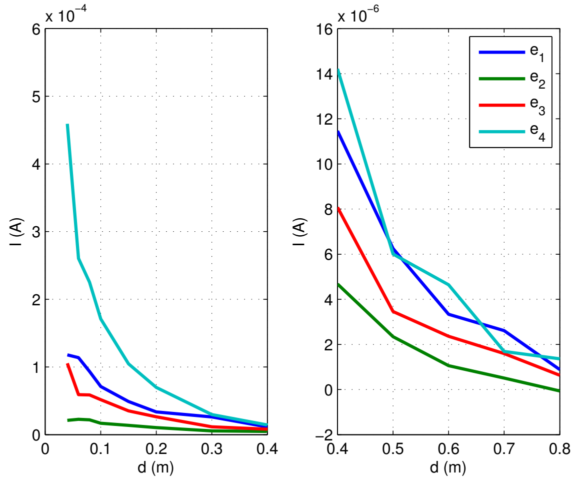

Fig. 10 Raw currents measured on the 4 electrodes of the passive aMussel while increasing the distance between the 2 aMussels.

$$
\begin{aligned}
I_{lat,1} &= \frac{(I_1 - I_2)}{2} \\
I_{lat,2} &= \frac{(I_3 - I_4)}{2} \\
I_{lat,3} &= \frac{(I_5 - I_6)}{2} \\
I_{ax,1} &= \frac{(I_1 + I_2)}{2} \\
I_{ax,2} &= \frac{(I_3 + I_4)}{2} \\
I_{ax,3} &= \frac{(I_5 + I_6)}{2}
\end{aligned}
\tag{7}
$$

And, we define $I_{lat} = \sum I_{lat,i}$, $I_{ax} = \sum I_{ax,i}$ $I_{ax,i}$ (axial current) represents the common part of the left and right currents flowing across the 2 electrodes of the macro-electrode i. The axial perturbative currents $I_{ax,i}$ is due to the variations of the total resistance of the scene. On the other hand, the lateral perturbative current $I_{lat,i}$ is proportional to the incident field. $I_{lat,i}$ (lateral current) represents the differential part of this left and right currents. This previous properties on $I_{ax,i}$ and $I_{lat,i}$ allows easily to determine some information of the environment. The axial current $I_{ax,i}$ is used to determine if the object is conductive or insulating. While the $I_{lat,i}$ currents is used to determine, with the knowledge on $I_{ax,i}$, if the object is on the left or on the right hand side of the sensor. When $I_{lat} = 0$, the sensor axis is necessarily aligned along the incident field (see table 1) Based on this 6 scalars defined in Eq. 7, by exploiting the morphology of the sensors (slender shape, bi-lateral symmetry), we can address the problem of navigation. A set of reactive control laws has been proposed [12], the 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 are used by fish that hunt by following the electric lines emitted by their prey [9]. If we assume that the robot is controlled using 2 parameters: its linear velocity V and its angular velocity Ω. We can apply the following control law on V, Ω (see figure 7):

$$V = C,$$
$$\Omega = K\, I_{lat}, \tag{8}$$

with C a constant positive value such that the sensor goes forward headlong and K a constant gain. By exploiting this control law, the robot just go straight at constant speed when there is not object in its surroundings but it will converge to an object or avoid an object depending on its electric properties (conducting and insulating) when such an object appears in its range of perception [5]. In more details the robot follows the electric line reflected by the polarized object as shown on figure 6.down. Depending on the object electric properties the measured values $\delta I_{ax} = I_{ax} - I(0)$ and I_{lat} varies following table 1.

Table 1 Sign of the perturbative axial and lateral currents δI_{ax} and I_{lat} with respect to the electric properties of the object and its side in the sensor frame. Currents were measured by the head electrodes when the object is in the frontal part of the sensor [5].

δI_{ax}	> 0	for a conducting object
δI_{ax}	< 0	for an insulating object
I_{lat}	> 0	for a conducting object on the left of the sensor or for an insulating object on the right of the sensor
I_{lat}	< 0	for a conducting object on the right of the sensor or for an insulating object on the left of the sensor
I_{lat}	$= 0$	for any contrasted object facing the sensor

It is worth noting that δI_{ax} and I_{lat} have a complementary role since the former can be used to determine if the object is conductive or insulating, while the latter allows us to determine if it is on the left or on the right hand side of the sensor. With our convention on the sign of the currents and angular velocities, taking $K > 0$ in (Eq. 8) ensures that when a conductive object is on the right (respectively on the left), the sensor turns to the right (respectively to the left). On the other hand, if the object is insulating and on the right (respectively the left), the control law makes it react as if there was a symmetric conductive object on the left (respectively the right). Thus, the controller repulsed the sensor from an insulating object. To invert the behavior, i.e. makes the sensor attracted by insulating objects and repulsed by conductive ones, the sign of K has to be changed in (Eq. 8). To summarize, depending on the parameter K, 4 reflex behaviours can be extracted:

1. **Reaching any object:** $K = k/\delta I_{ax}$, with $k > 0$,
2. **Avoid any object:** $K = k/\delta I_{ax}$, with $k < 0$,
3. **Reach conductive objects/avoid insulating objects:** $K = k/\mid \delta I_{ax} \mid$, with $k > 0$,
4. **Reach insulating objects/avoid conductive objects:** $K = k/\mid \delta I_{ax} \mid$, with $k < 0$.

On figure 11 an illustration of the behaviour "reaching an object" is applied when going from A to B. It has be clearly demonstrated in [5] that these behaviours can be use to navigate autonomously reaching or avoiding obstacles. It has be mentioned that all these behaviours are fully reactive and do not need any prior knowledge.

5.3 Reactive navigation using active electric sense (memory based)

In the previous section we presented control strategies allowing the sensor to reach or avoid objects, here we will describe how to turn around an object based on the fact that we "recognized" it. This behaviour is based on a combination of reflex behaviours presented in the previous part. By sequentially ordering 3 reflexes we seek an object and then turns around it (see figure 11 from [13]).

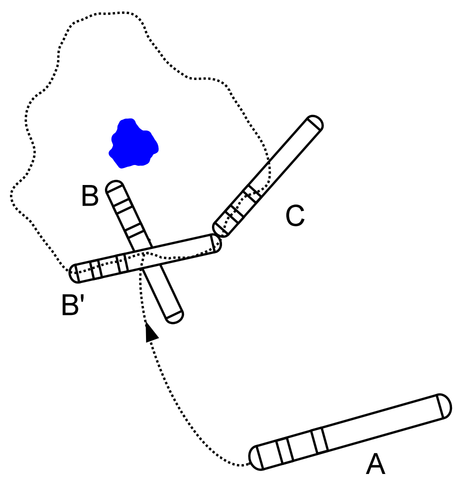

Fig. 11 Object exploration based on electric sense. It has to be mentioned on this illustration that the object is a conductive object [13].

1. **Seek an object:** From A to B on figure 11 the robot is seeking an electrically non-transparent object by applying the attractive behavior with $K = k/\delta I_{ax,1}$ and $k > 0$. This behavior is maintained until $\delta I_{ax,2}$ changes its sign. The reason of this is that when getting closer to an object, more and more electric field lines are captured by the object if it is conductive. Thus, the electric field lines are concentrated on the front electrodes. On the contrary, if the object is insulating the electric field lines are pushed backward along the sensor axis. Thus, in both cases at some point $I_{ax,2}$ changes of sign.
2. **Flee from the electric influence:** From B to B' on figure 11. It corresponds to the initialization of the orbiting motion of the sensor around the object. It is obtained by applying the repulsive behavior, i.e. $K = k/ \mid \delta I_{ax,1} \mid$ and $k > 0$ until $\mid \delta I_{ax,1} \mid$ reach its minimum.

3. **Follow the boundaries:** From B' to C on figure 11. The orbiting phase is obtained by applying the law $\Omega = K(\delta I_{ax,1} - M)$. M is the value of $\delta I_{ax,1}$ measured at the last time of the previous phase.

It has to noted that the commutation between phases is ruled by events which only depend on time variation of the measurements (and not of their magnitude). Such a behaviour completely developed in [13] shows that the robot can navigate avoiding, reaching and turning around objects only using active electric sense.

5.4 Reach an active robot by controlling a passive robot

We consider here a passive robot that tracks the electric lines of an electric field generated by another active robot. On figure 12.a, 2 external electrodes: emitter (circle 1) and receiver (circle 2) are representing the active robot that can be considered as a docking station [4]. These electrodes are close to each other and located in one of the corners of the tank. By using the same reflex behaviours presented in the previous section we can navigate with a passive robot. This results is shown on figure 12 where the passive robot reach an emitter with 3 different starting positions [4]. The sensor's path is represented by a dotted lines and letters correspond to intermediate poses. For all position on figure 12.a, the current I_{ax} is positive along the path and monotonically increases (figure 12.b). On the other hand, I_{lat} converges toward its desired zero-value. The changing sign is due to the presence of the perturbative repulsive walls (from 0 to C and from 0 to B) the probe to far from the emitter first avoid the insulating walls and converge towards the emitter as it is getting closer. As shown the robot is docking on the emitter in all 3 cases with different trajectories. This experiment first presented in [4] show that navigation of a passive robot in the electric field generated by an active is also possible.

5.5 Object localization and recognition from an active robot

In this section we consider an active robot and an object in its range of perception than is electrically contrasted with the water (see figure 6). Our robot is moving straight alongside of the object (see figure 13) and we collect every millimeters 6 currents gathered in I_{lat}, and δI_{ax} (see Section 5.2). Our goal here is to estimate the localization, the pose and the size the object O_x that perturbates the electric field generated by the robot. To simplify the problem we will solve the problem only in 2D and we supposed that: the conductivity of the medium γ is known as well as the displacement of the robot along its trajectory in a global reference frame. We performed experiments with a conductive prolate ellipsoid (i.e. axisymmetric about its major axis), i.e., that can be described by 6 parameters: its localization x_0, y_0, its orientation θ_0, its size a, b and its electric properties (conductive or insulating) σ. Based on Section 5.2 we can already estimate the electric properties of the object

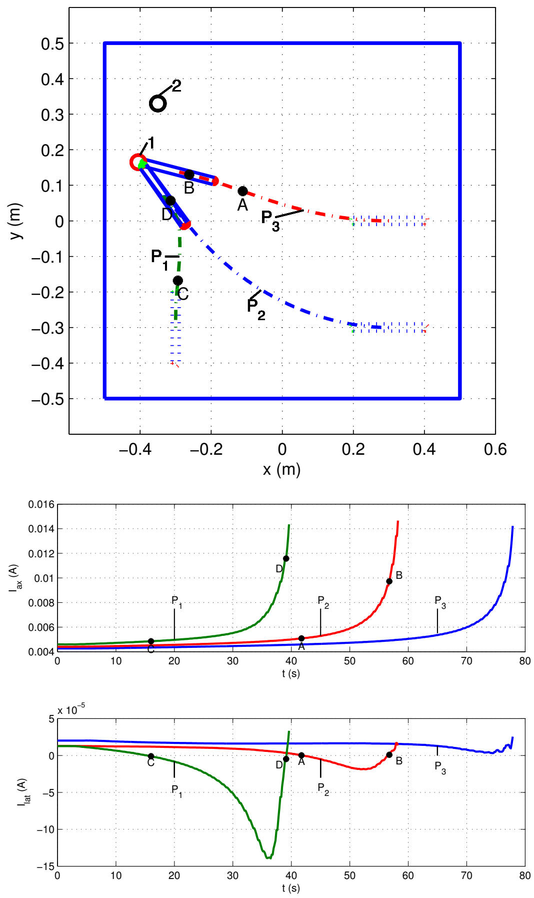

Fig. 12 Starting from 3 different initial poses (dashed lines), the sensor seeks the emitter until it touches it following 3 paths (a) Scene and paths P1, P2 and P3. (b) Axial currents (I_{ax}) and (c) lateral currents (δI_{lat}) for the 3 paths. A, B, C, D indicate poses where the sign of lateral currents change [4].

σ and its side with respect to the robot as soon as the object enter in the perception range of the robot. This can be obtained looking at the sign of δI_{ax} and I_{lat}. Then, based on these information, we will estimate the missing parameters by using a greedy problem solving heuristic testing a set of potential solution in the parameter space and select the optimal solution. This method is based on the analytical model presented in [3] that models the dipolar electric response of an object immersed in a electric field produced by the robot of figure 7. Within this analytical we modeled the ellipsoidal object by its first order polarization tensor [1][11]. Giving this analytical model, we implemented a function f that receives as parameters: a robot position (x_k, y_k, θ_k) along the trajectory $T(k)$ and an object O_x in a global reference frame.

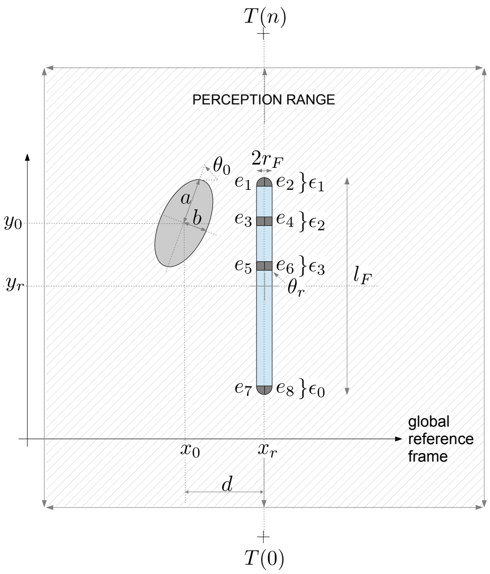

Fig. 13 Experiment set up with the aFish.

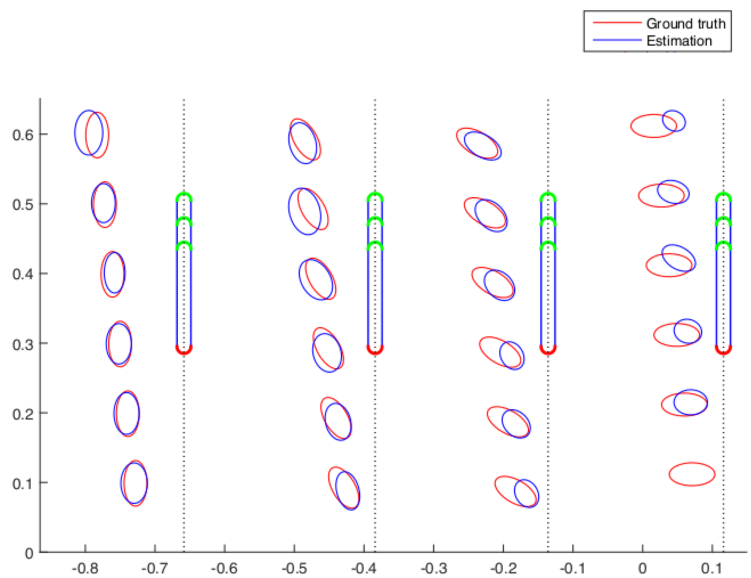

Fig. 14 Localization and estimation of a 33×16 conductive ellipsoid at 5 different distance. Real ellipses (red), estimates (blue).

The function returns the 6 currents described in Eq. 7. This function that estimates 6 values we named $\widehat{I(k)}$ can be expressed as: $\forall$k$\in [1,n]$ we have:

$$f(T(k),O_x) = \widehat{I(k)} = \begin{pmatrix} I_{lat}(T(k),O_x) \\ \delta I_{ax}(T(k),O_x) \end{pmatrix} \tag{9}$$

where k is a position along the trajectory $T(k)$ that is discretized into n positions. Finally, to estimate the ellipsoid that perturbates the electric field we compare for a set of possible object parameters the sum of the error between the real measurements and the estimated measures for each robot positions. The object with the smallest error is then chosen as the solution of our problem. This algorithm can be summarized by: the Eq. 10.

$$\underset{0_x}{\operatorname{argmin}} \sum_{k=1}^{n} \left(\sum_{i=1}^{6} \frac{|I_i(k) - f_i(T(k),O_x)|}{|I_i(k)|} \right) \tag{10}$$

Figure 14 shows 24 experiments performed with an conductive ellipsoid which size was 33×16 mm. The real ellipses are displayed in red and the estimated ellipses in blue. Each results has been obtained offline using data collected by the robot (following a straight line trajectory) at different 6 distances $50, 60, 70, 80, 90, 100$mm and with 4 different object orientations. As it can be seen the localization and the shape can be estimated at a short distance. As we increase the distance with the object the recognition is unfortunately getting worst as the signal noise ratio decreases. It has to be noted that for the presented results the resolution for the localization and the shape estimate was 2mm and the angle resolution was 0.26 radians. Such a greedy method can be used to estimate our object in an acceptable time (few minutes) because all parameters are quite well constrained by the model assumption and the small range of the sensor. The position x_0, y_0 are constrained by the range of the sensor which is about the sensor length l, so $x_0 \in [-l, +l]$, and $y_0 \in [0, \pm l]$. As well, $\theta_0 \in [0, \pi]$. Then, the maximum size of the object is also known as our model consider small object (smaller than the robot length l). Then, the only parameter of the algorithm is the discretization step of the each parameters. In this last section we shown that just using electric sense we can also localize and estimate the shape of an object.

6 Conclusion

In this paper, we presented an overview of electric sense based perception and navigation algorithms for the underwater robots that will be used in the context of the EU project subCULTron. We presented different algorithms based on electric sense that will be used by our robots to perform reactive navigation, obstacles avoidance, objects exploration and finally object shape estimation. These methods have been illustrated by some simulation and experimental results. From these results we can conclude that in many cases electric sense can supplement common underwater sensing devices in harsh conditions that is to say confined, low light and turbid underwater environment. In the new future, this work on electric sense will be extended towards collective based behaviours and localization and mapping (SLAM).

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`http://www.subcultron.eu`.

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