COOPERATION

ANGELS
ANGUILLIFORM ROBOTWITH ELECTRIC SENSE

Un sens nouveau pour la navigation des véhicules sous-marins en milieu difficile : le sens électrique

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ARMINES

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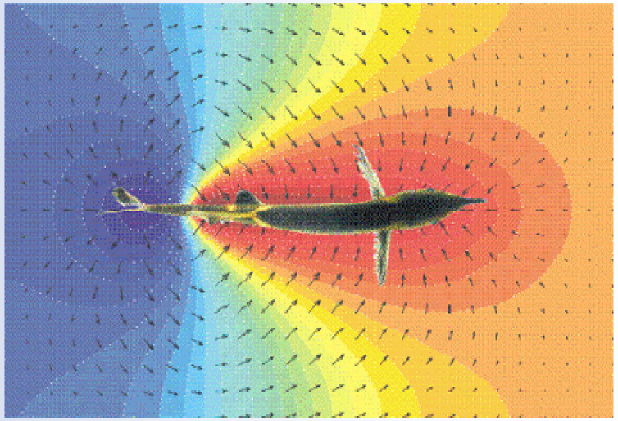
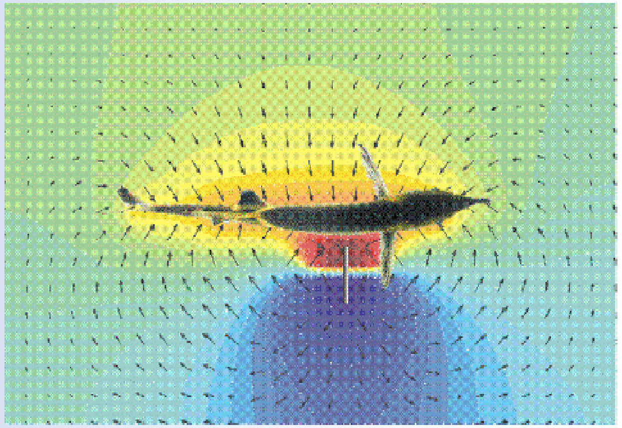
What is electric sense?

In order to perceive its environment, the fish polarizes two regions of its body…

Gnathonemus petersii

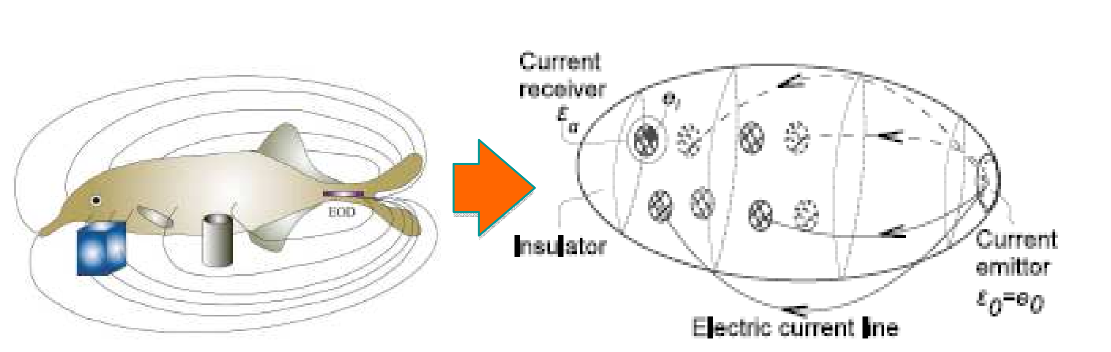




By comparing the currents crossing the skin with and without objects, the fish perceives the objects (shape, locations, electric colors…)

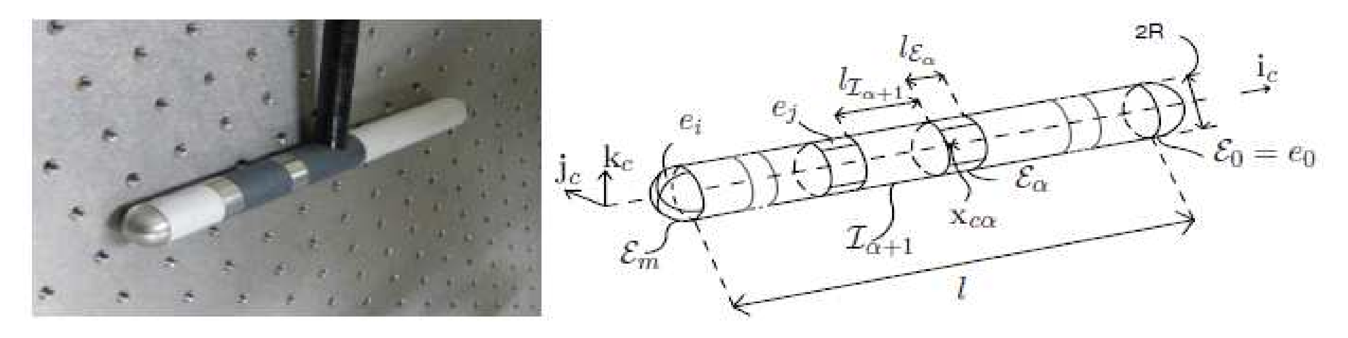
The electric sensor

Bio-inspired approach…



African dipolar fish

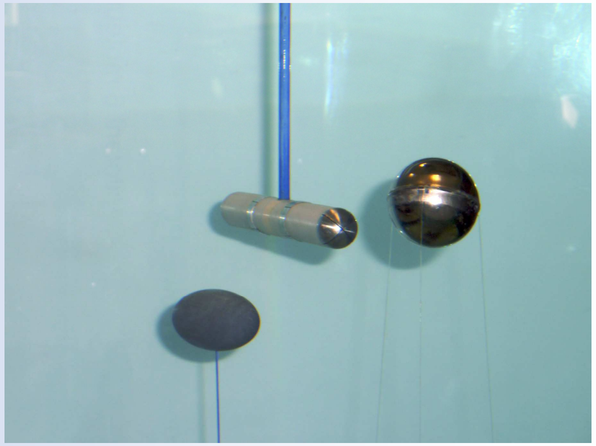
Physical principle: U imposed, I measured



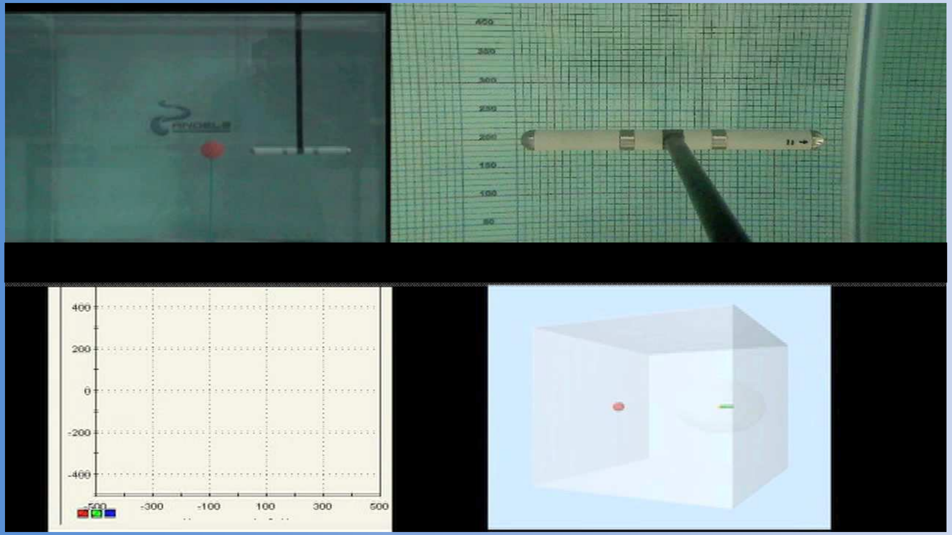
… based on this principle, we have built a set of slender probes… (ARMINES) [IEEE Sensor, sub.]

Electrolocation test bed

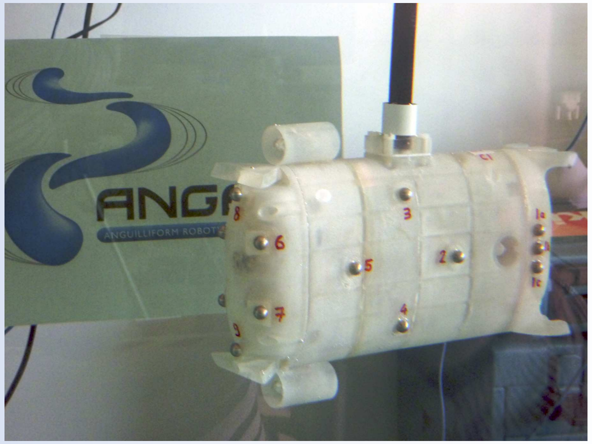
Electric sensor test-bed



Object electrolocation



dSPACE rapid control prototyping device

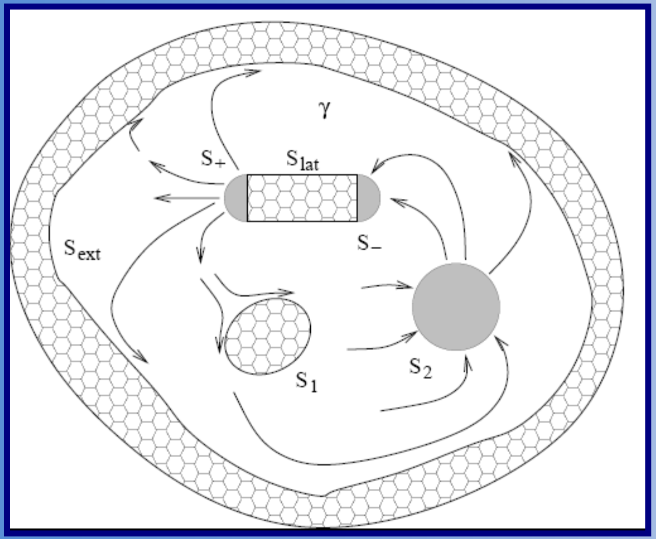


ANGELS module (SSSA)
+ electric sensor (ARMINES)

Inverse electric problem

Any electrolocation algorithm has to solve the inverse electric problem…

Originally, it appeared as the most difficult theoretical one that Angels addresses.



Basically, it can be stated as follows:

1°) First formulation:

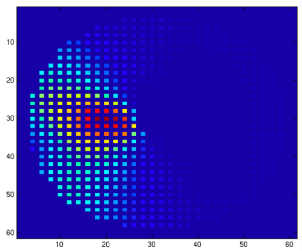
“Find γ such that in the scene :

$$\nabla.(\gamma\,\nabla\phi)=0$$

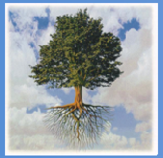
For Bc imposed and measured on the sensor.”

Inverse problem ⟷ Impedance – Tomography problem

EEG algorithms



From CVLab (EPFL)



Inverse electric problem

Too costly to be used on-line… → Reduction of the parametric space

→ γ constant on sub-domains

$$\Delta\phi = 0 + \text{BC of sensor} + \text{B. crossing C}$$

Considering simple shaped objects → alytic solutions …

→ 2°) Second formulation:

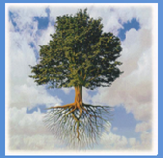
“ Find p *and* γ *such that the electric matrix equation*:

$$U = R(p,\gamma)I$$

For any U *and* I *respectively imposed and measured.”*

→ Inverse problem ↔ Finite dimensional non linear problem

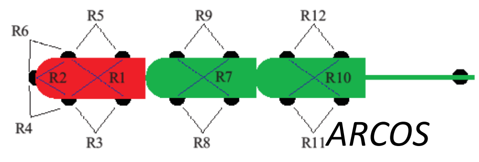
→ Solvable with classical nonlinear control techniques…



Inverse electric problem

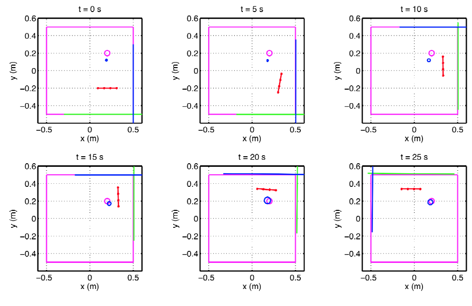
We begun by adopting…

- For object recognition → learning based approach →



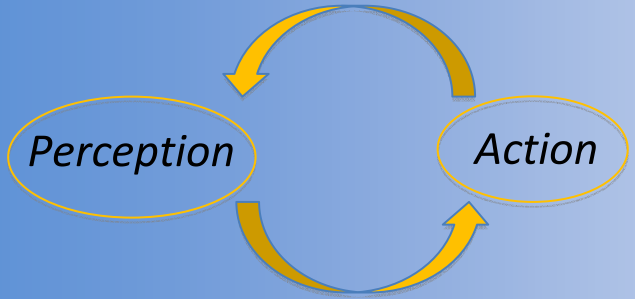
- For navigation → Kalman filtering based approach [IJRR, sub.]…

… gave first encouraging results but some limitations arose: →



- Requires an analytical model of the scene
- Due to the sensor range, it requires to change the state dimension …

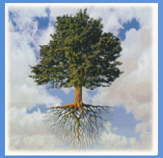
→ Limitations became a serious drawback due to the increasing complexity of the project (complex scenes, multi-agent…).



Perception

Action

→ Solution: Use a reactive approach!

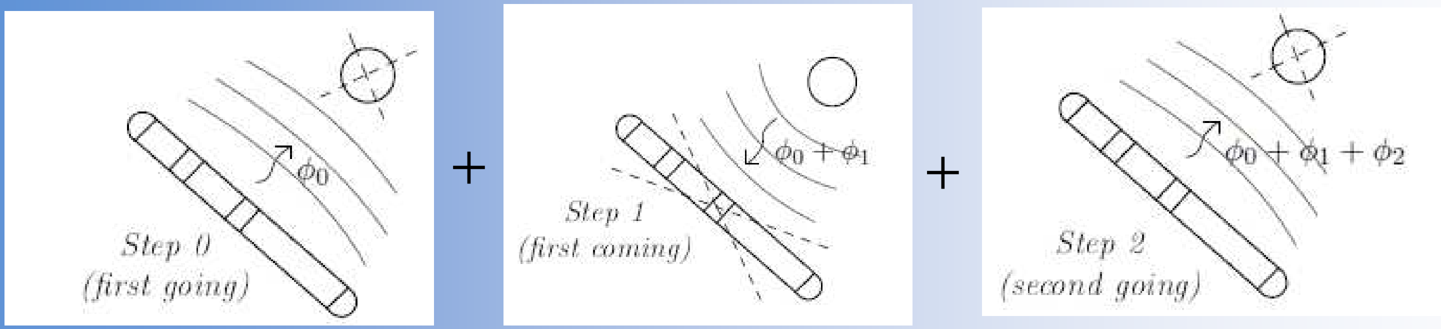


Exploitation of action-perception synergies

1°) Deeper understanding of models [IEEE TRO 2012] based on:

– Method of reflections: Interactions sensor-object = $\sum$ successive reflections

$$I = I^{(0)} + I^{(1)} + I^{(2)}$$, where:



+...

$I^{(0)} =$ currents with no object

$I^{(1)} =$ currents reflected by the object with no sensor

$I^{(2)} =$ currents generated by the electric response of the sensor to the first reflection

– Exploitation of the morphology of the sensor:

Bilateral symmetry: $I = I_{ax} \oplus I_{lat}$, Slenderness: $I_{lat} \sim \Phi_{lat}(\vec{E}_{(1)})$

Axial currents

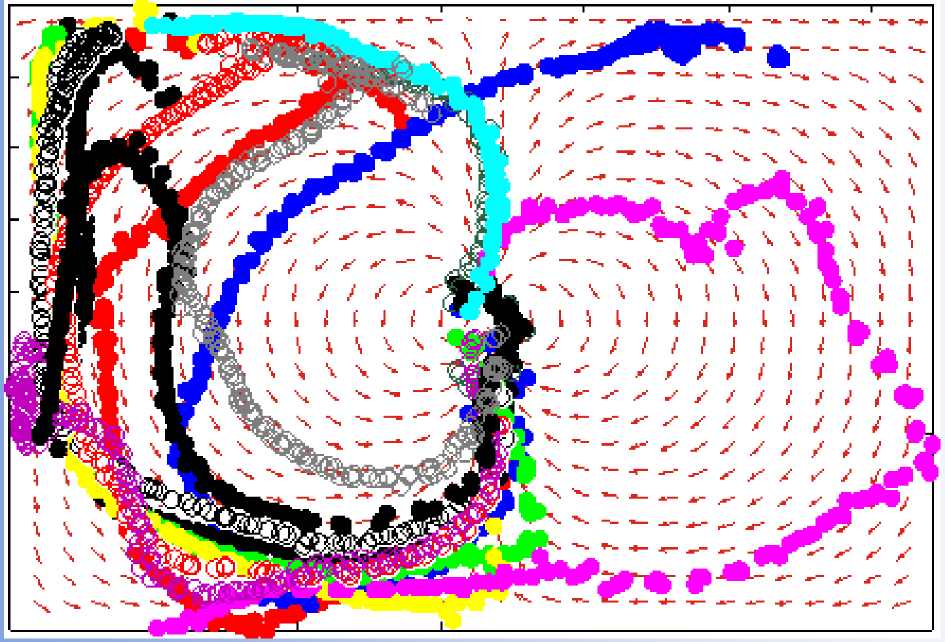
Lateral currents

Bio-inspiration

I_{ax} tells us if object is conductive or insulating, : I_{lat} if it is on left or right

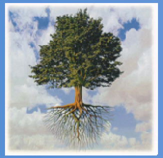
Exploitation of action-perception synergies

2°) Coming back to the nature…



From IIBCE

The idea consists in implementing this navigation strategy on the rigid modules…



Reactive navigation

In order to achieve this navigation strategy [IEEE TRO sub.]…

- Remove the basal component $I^{(0)}$ from measurements
- Apply the control law:

$$\boxed{V = cte, \quad \omega = k\ I_{lat}}$$

$I_{lat} \sim \Phi_{lat}(\vec{E}_{(1)})$

The sensor aligns
on the current lines.

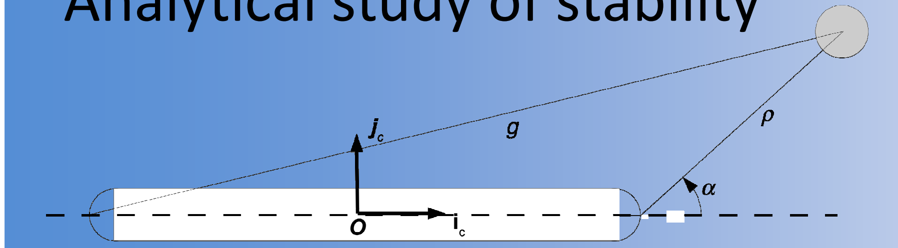
With simple $k = k(I_{ax})$, one can encode relevant navigation behaviors, as :

- Seeking conducting objects
- Avoiding insulating obstacles

Method of potentials where
Potentials are not virtual but real

Exploitation of action-perception synergies

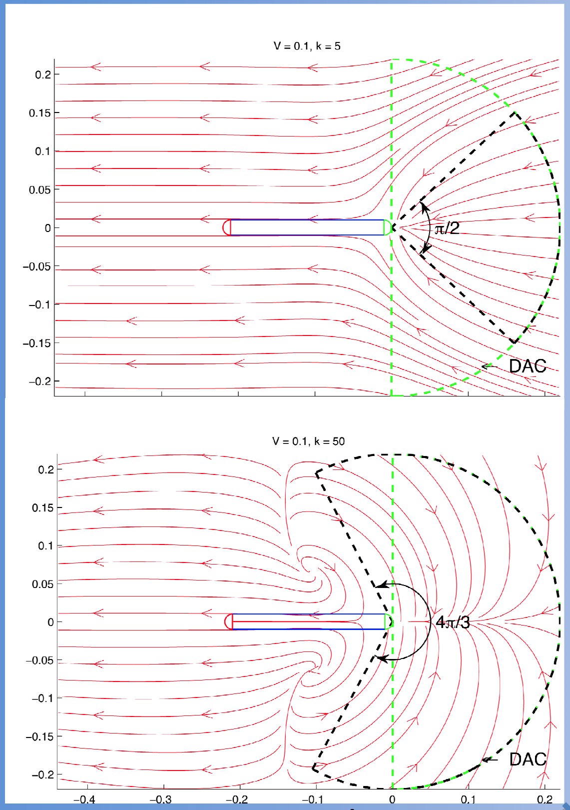
Analytical study of stability



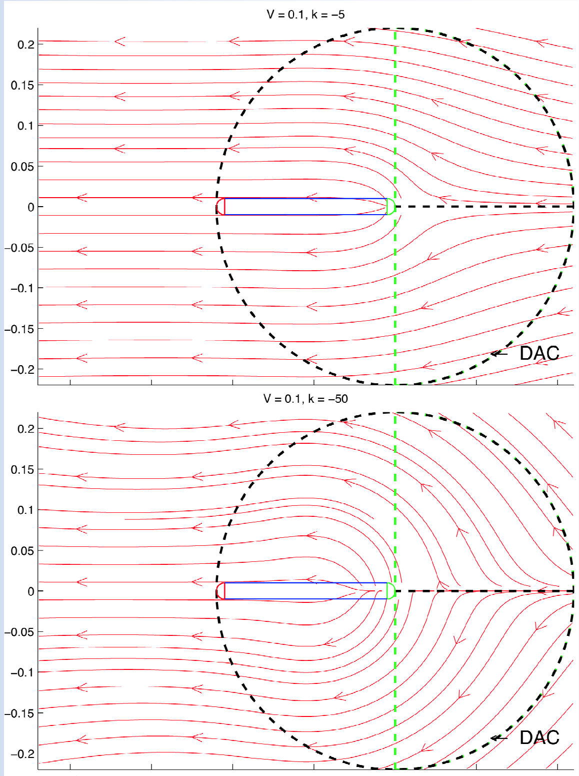
Using the method of reflexions...

Closed loop Kinematics:

$$\begin{cases} \dot{\rho} = -cos\alpha V - \frac{l}{2}\left(\frac{kAf}{\rho Bh}\right) sin\alpha^2 \\ \dot{\alpha} = \frac{sin\alpha}{\rho} V - \left(1 + \frac{lcos\alpha}{2\rho}\right)\left(\frac{kAf}{\rho Bh}\right) sin\alpha \end{cases}$$

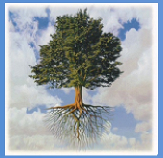


Attractive law



Repulsive law

Reactivity increases with *k/V*



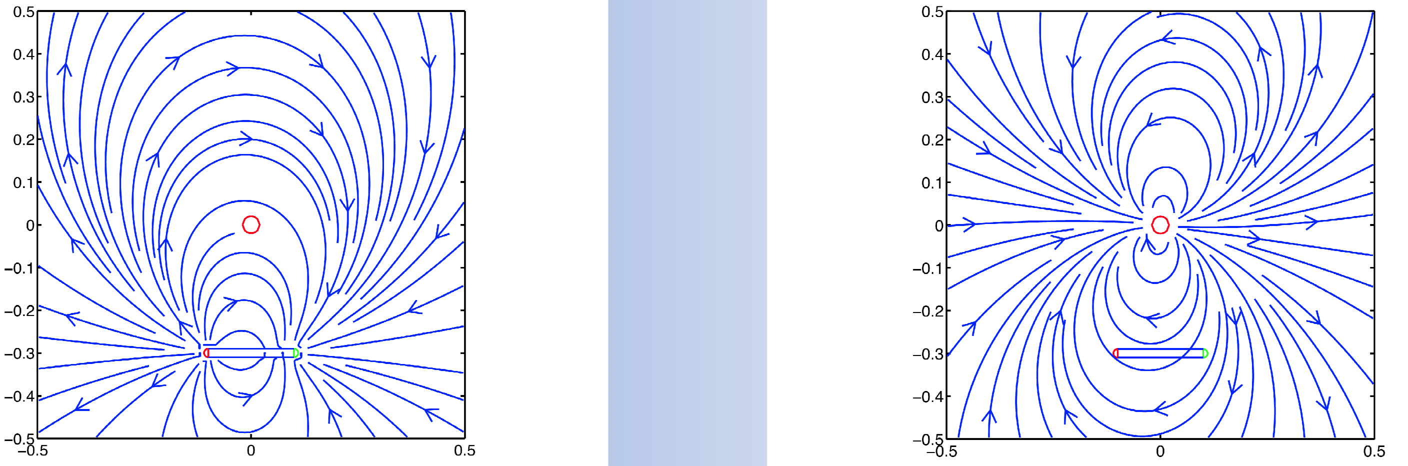
Exploitation of action-perception synergies

Simulations

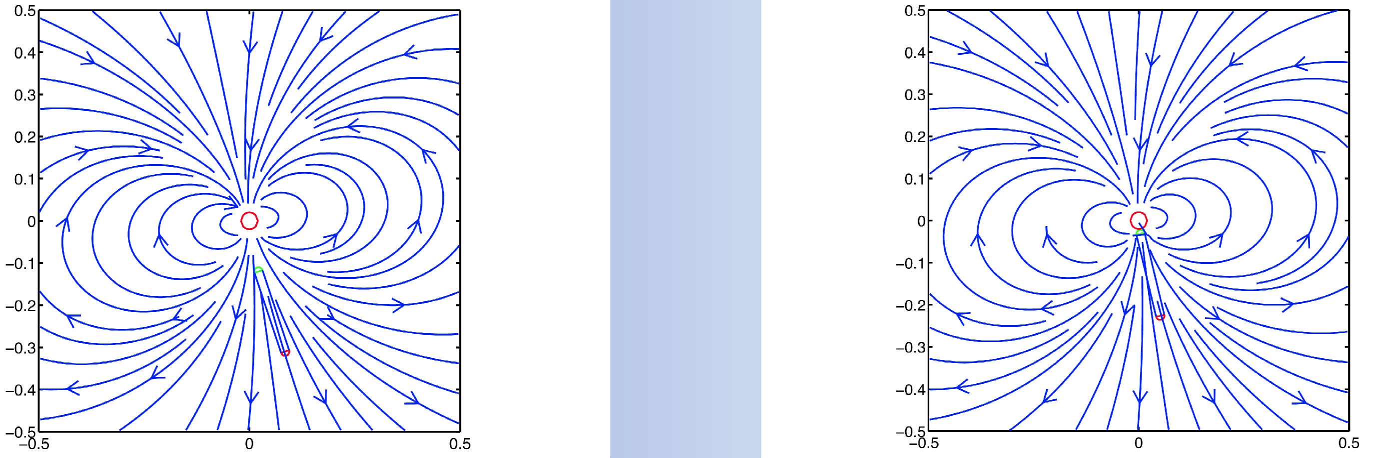
Behaviour = seeking conductors and avoiding insulators

Exploitation of action-perception synergies

Seeking a conductive object



Portrait of the total electric field



Portrait of the perturbative component of the field

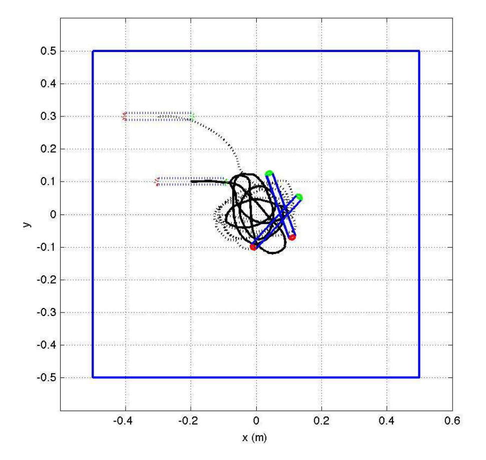
Exploitation of action-perception synergies

Experiments

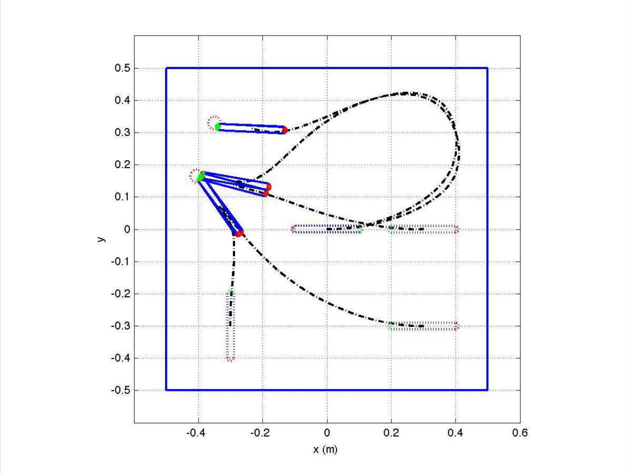
Behaviour = Seeking conductors and avoiding insultors

Exploitation of action-perception synergies

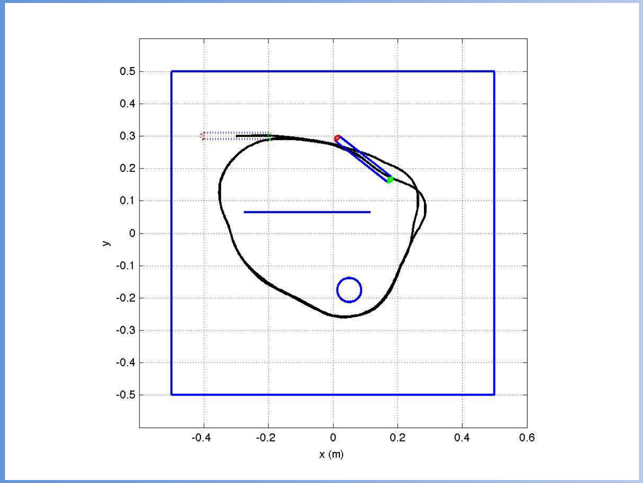
Seeking conductors and avoiding insultors: experiments



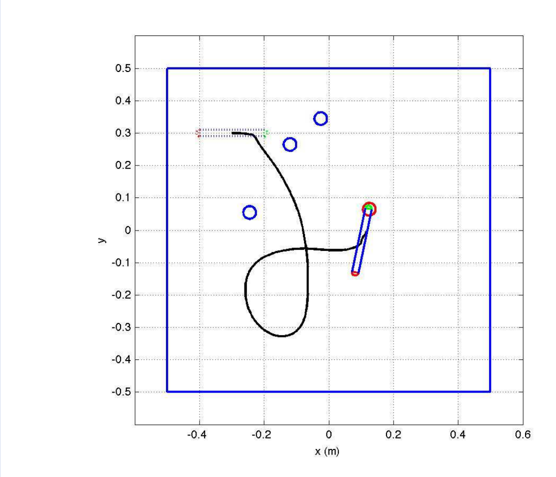
Tank with no object



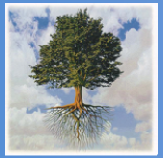
Tank with an active dipole



Tank with 2 insulators



Tank + 3 insulators + 1 conduct.



Exploitation of action-perception synergies

From memory-less to mnesic reactive control

New perspective to the pb of underwater navigation in confined environments…

- requires no model → can be applied to Angels module (bilateral symmetry)
- the electric field is an extension of the body of the robot (embodiment)
- exploits the haptic modality of electric sense
- Sensory-motor loops exploiting perception-action synergies (solve inverse pb by navigation)
- ~~Virtual~~ “Real" potential field approach for underwater navigation
- Memory – less reactive control
- uses only two measurements (head) electrodes (binocular sensor)

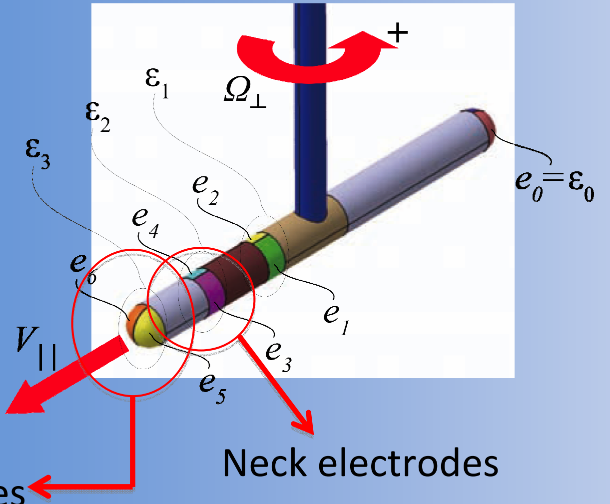
If we enrich the measurements with neck electrodes (depth)…

- We can design mnesic reactive laws encoding more complex behaviors as “object exploration”…

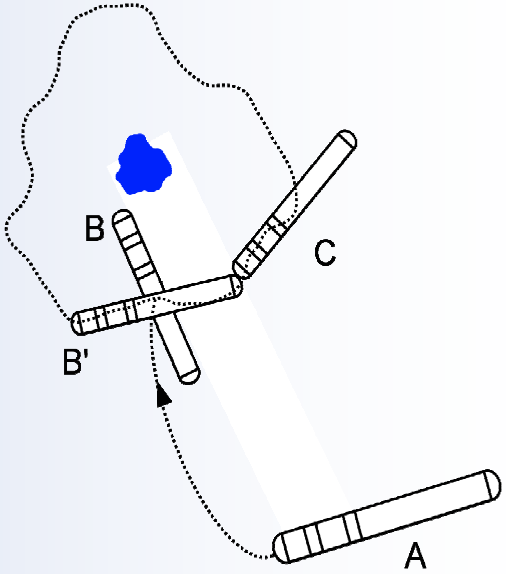
Exploitation of action-perception synergies

Reactive law for exploration of objects

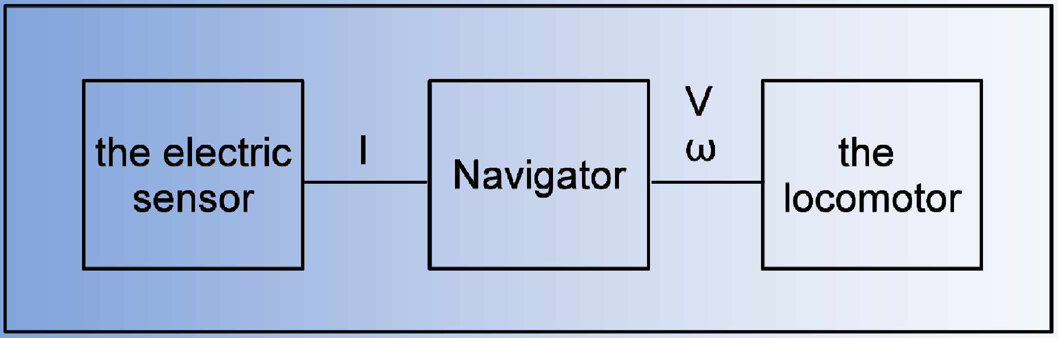
Sensor:



New behavior:



General architecture for navigation



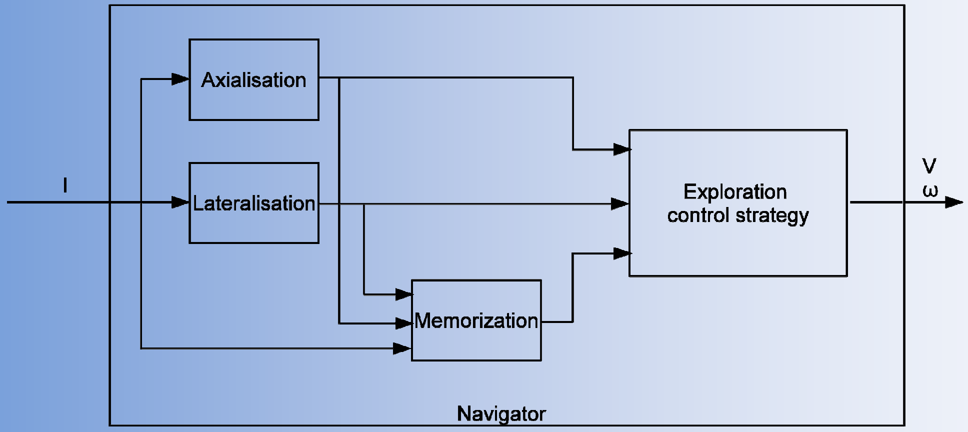
the electric sensor → Navigator → the locomotor

Embarked on the underwater robot

Exploitation of action-perception synergies

Reactive law for exploration of objects

Navigator



It includes:

- A sub-block “Axialization” which sum the currents of the same ring.
- A sub-block “Lateralization” which subtract left and right currents of each ring
- A sub-block “Memorization” which memorizes certain values taken by the measurements along the motion of the sensor.

Exploitation of action-perception synergies

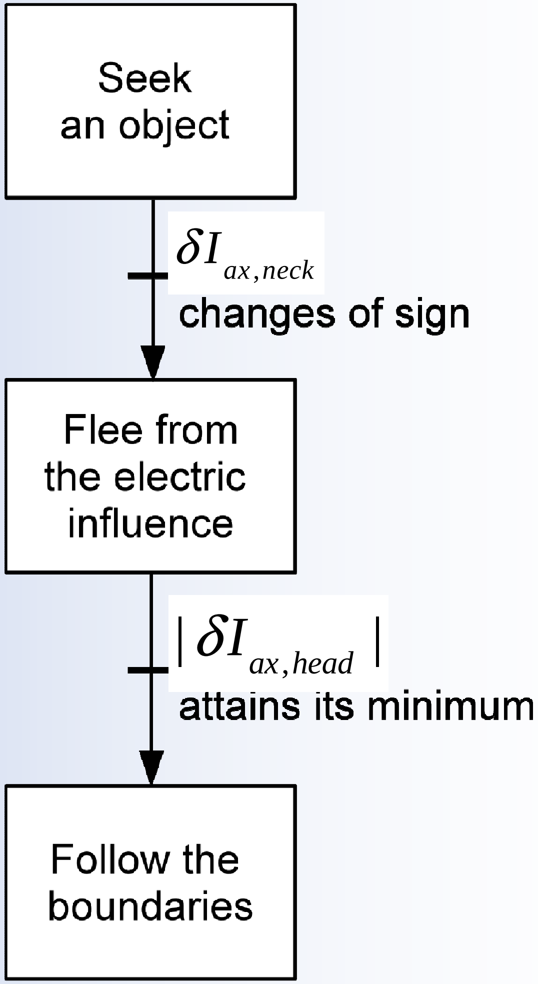
Reactive law for exploration of objects

1) Memory-less attractive law

2) Memory-less repulsive law

3) Follow the boundaries of the object.

$$V_P = C > 0 \qquad \Omega_\perp = k\left(\delta I_{ax,head} - \delta I^{mem}_{ax,head}\right)$$



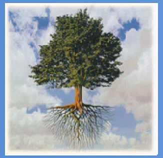
Seek an object

$\delta I_{ax,neck}$ changes of sign

Flee from the electric influence

$|\delta I_{ax,head}|$ attains its minimum

Follow the boundaries

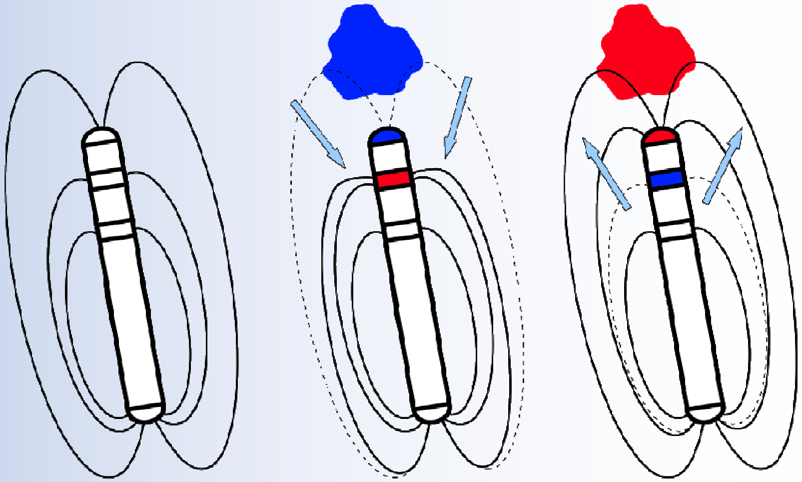


Reactive law for exploration of objects

Interpretation of the commutation between behaviors

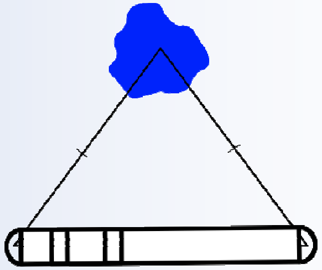
« $\delta I_{ax,neck}$ changes of sign »

« The electric lines are pushed forward and backward depending if the object facing the sensor is conducting or insulating »



« $|\delta I_{ax,head}|$ attains a minimum »

« When the head and tail electrodes are equidistant of the object, the head currents attain a minimum »

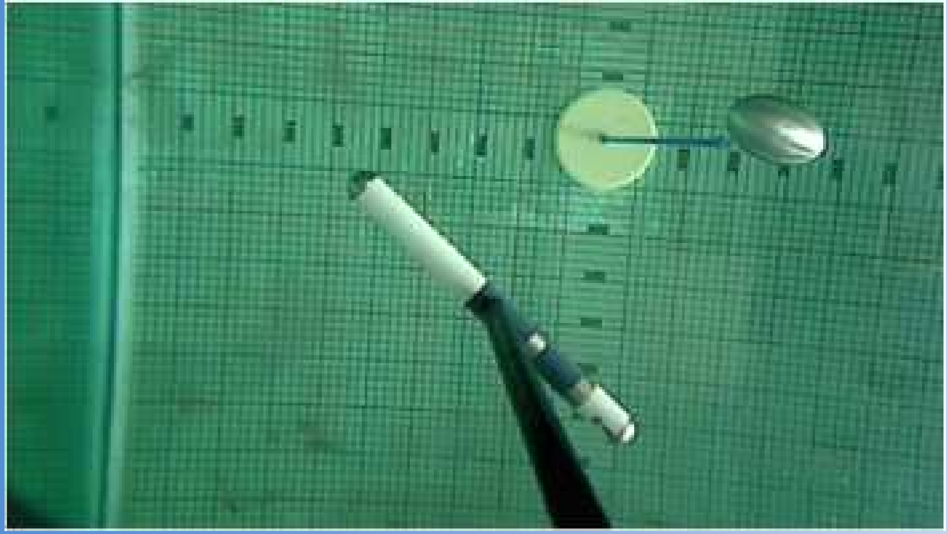


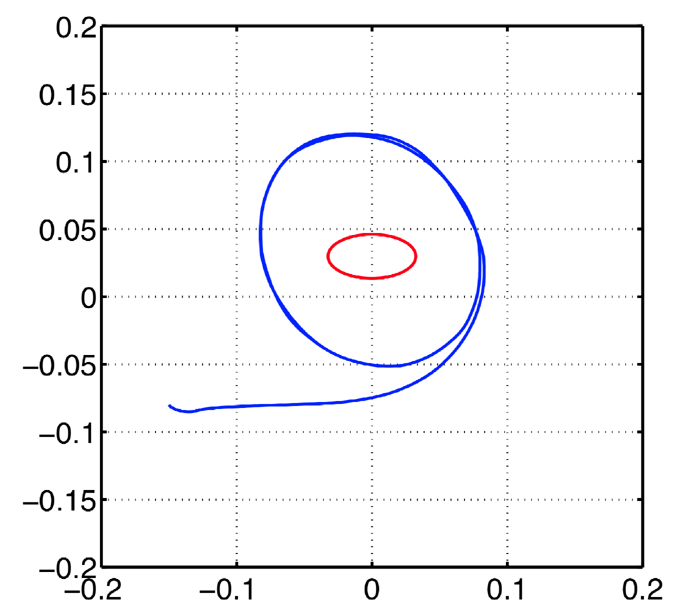
Electric sensing

Exploitation of action-perception synergies

Experimental results

➡ Exploration of a small objects…



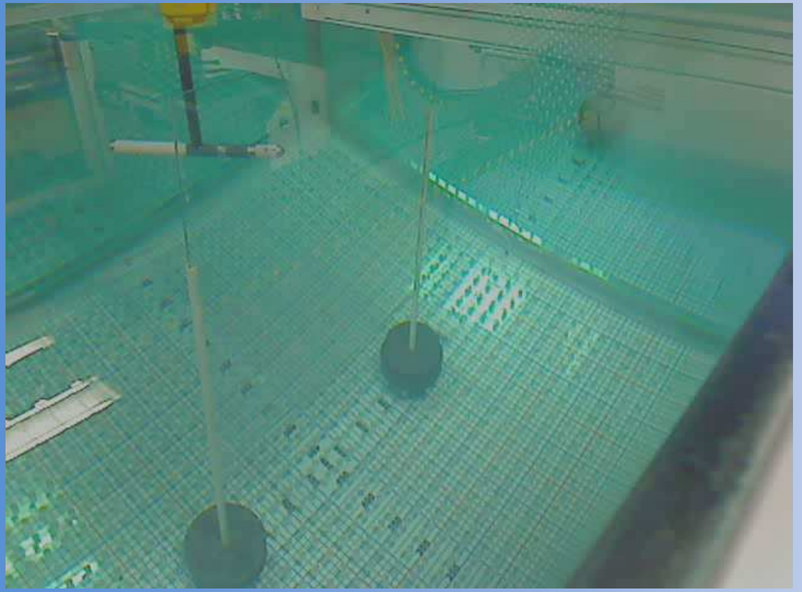


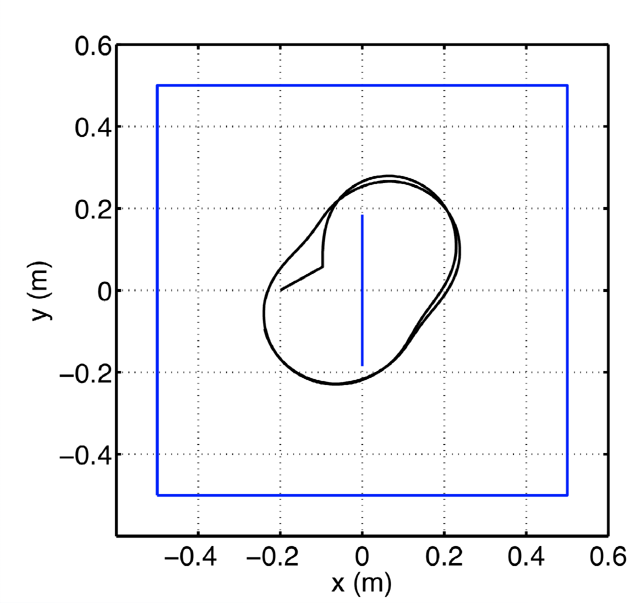
Electric sensing

Exploitation of action-perception synergies

Experimental results

➡ Exploration of a large objects



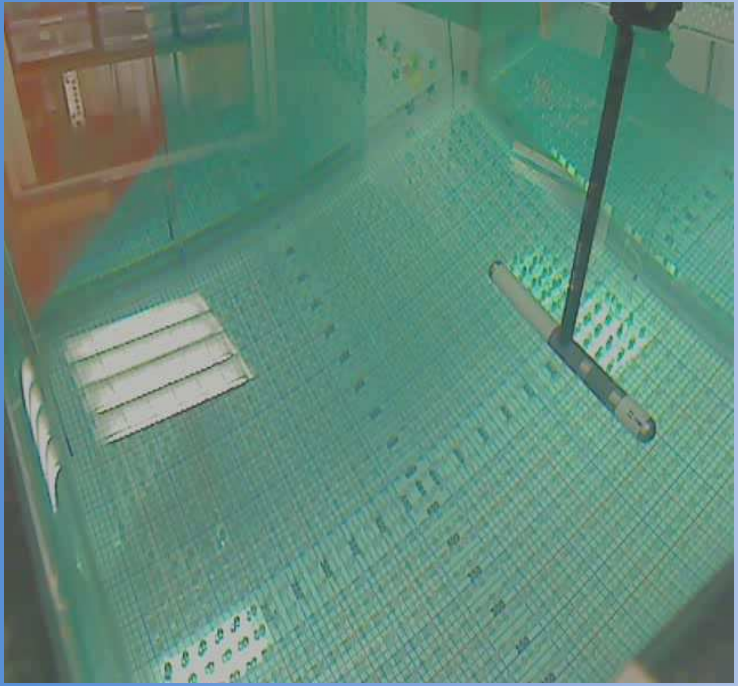


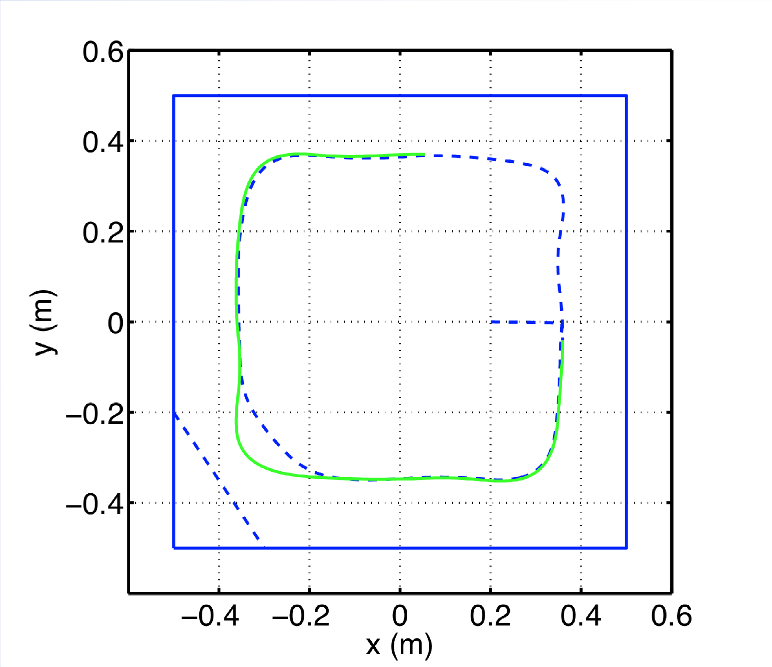
Electric sensing

Exploitation of action-perception synergies

Experimental results

➡ Exploration of a large object (wall following)





Exploitation of action-perception synergies

With the Angels module…

www.theangelsproject.eu

Autonomous navigation with electrolocation

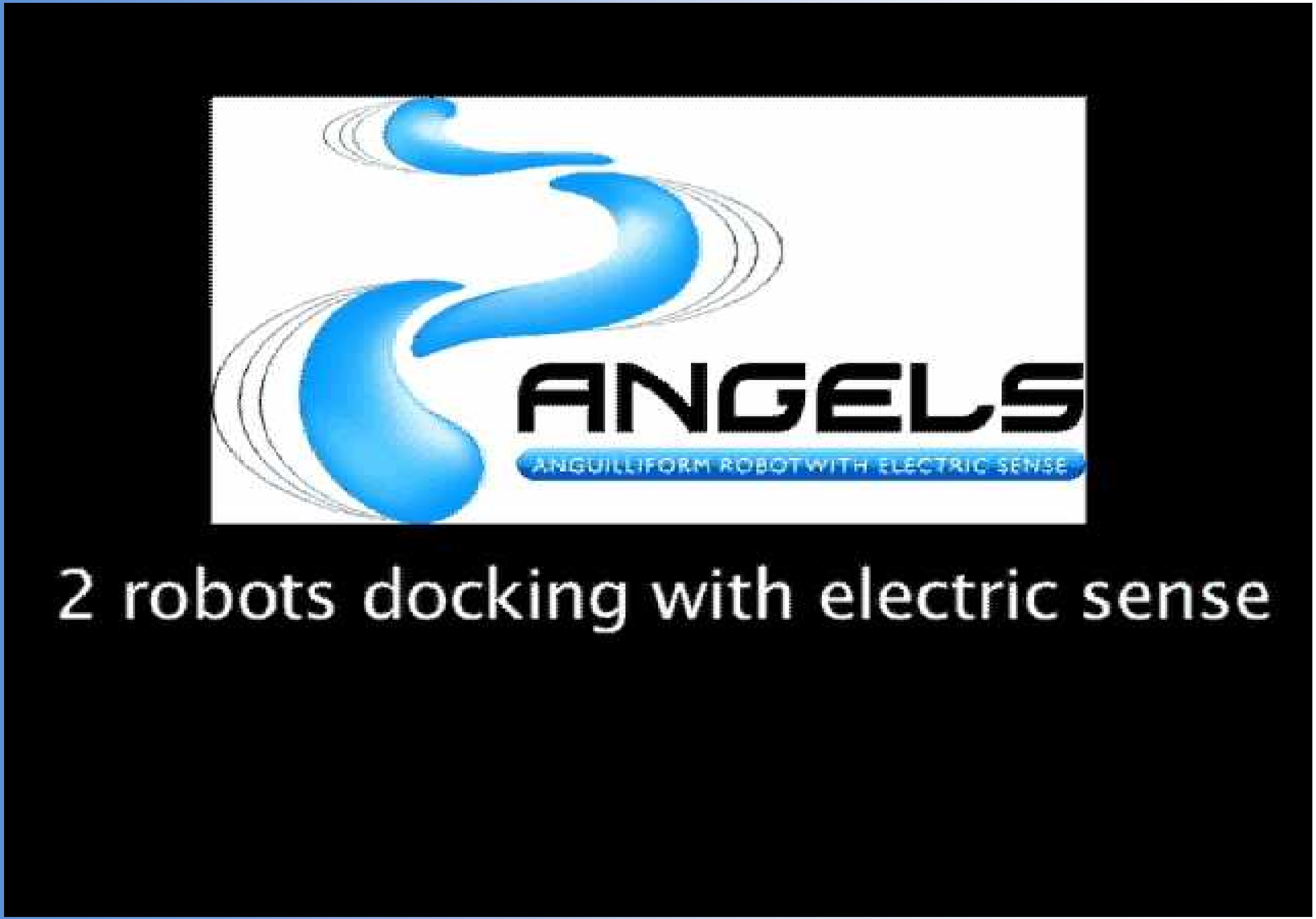
Integration with electric sense

ANGELS

ANGUILLIFORM ROBOT WITH ELECTRIC SENSE

Reactive navigation
Behaviour :
– avoiding insulators
– seeking conductors

Integration with electric sense



2 robots docking with electric sense