# PhD 2nd Year Progress Report
# Fr-UK Joint PhD Programme

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**Title:** Exploration of a large underwater area with autonomous vehicles
**FR university:** ENSTA Bretagne (Luc Jaulin, Fabrice Le Bars)
**UK university:** University of Sheffield (Lyudmila Mihaylova, Sandor M. Veres)
**PhD dates:** October 2014 — December 2017

## 1 Agreement between the 2 Universities

This agreement with the University of Sheffield introduces a new relationship with the Lab-STICC (ENSTA Bretagne). Both universities use tools based on Interval Analysis [10, 13]. This PhD is a good opportunity to develop new methods in this field. Here, emerging approaches are illustrated by concrete applications of Autonomous Underwater Vehicles (AUV) localization with real datasets.

## 2 Abstract – Short Summary of Research

### 2.1 Initial subject

This thesis considers a group of $n$ low-cost underwater robots that have to explore a wide area (seabed mapping). Robots are not allowed to surface (except at the beginning and at the end of the mission) and should organize themselves in order to perform the exploration without being lost. The main objective of the group is to build a reliable sonar/optical image (or a mosaic) of the seafloor without any hole in the image. To build such an image it is important to limit as much as possible the drift generated by the dead reckoning localization. This drift is particularly important for low-cost robots which are not equipped with loch-doppler sensors and accurate gyroscopes.

Now, the drift can theoretically be controlled using SLAM (Simultaneous Localization And Mapping) techniques [9]. Since the seabed is not structured, it is particularly difficult to detect automatically reliable seamarks that are needed to perform the SLAM. What we propose here is to use some of the robots of the swarm as *anchors*. The other robots are called *explorers*. To scan a large area, roles of anchors and explorers will alternate with the evolution of the mission. This strategy of exploration is called a *walking strategy*, where foot steps are performed by anchors. In a submarine context, we can also assume that robots can measure distances between them using the time flight of sound. With this technique, we hope that we will avoid the localization drift due to time and limit significantly the drift in space.

The objective of this thesis is to develop estimation and control methods in order to perform a reliable and accurate image of the environment, using a walking technique.

### 2.2 Workflow

Before going any further, we decided to focus on the beginning of the exploration mission. We developed a new method to localize a deep object from the surface – Section 3.1. This will provide an absolute localization for the *walking strategy* introduced in Section 2.1. The approach reveals the need to develop new academic tools to handle inter-temporal measurements – Section 3.2 – and a new guaranteed integration method – Section 3.3. These tools will be applied to the *walking strategy* – Section 5.2 – as well as a new localization method based on loop closure in robots trajectories – Section 5.1.

# 3 Presentation of first results

## 3.1 Localization based on symmetry properties

Before looking at the exploration itself, we decided to consider the beginning of the mission: the transition phase from the surface to the seabed. Typically, exploring a wide underwater area is relevant in oceans. Hence, robots will have to perform the exploration in very-deep areas (several *km*). Today, because of unusable GNSS and difficulties due to underwater acoustics, it remains a challenge to localize a deeply based object from the surface. This is however required to start an absolute localization, needed to perform the exploration of the wide underwater area.

A deep environment means strong uncertainties about its composition (temperature, salinity, pressure, etc.). This leads to a bad knowledge of sound celerity profiles, needed to compute distances and thus to perform localizations. We worked on a new state estimation method based on symmetry assumptions we can typically encounter in marine environments. This work introduces a research on **inter-temporal measurements** that will be the common thread of this PhD.

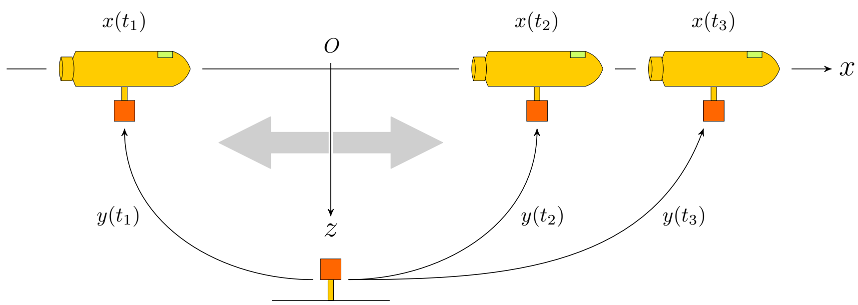


Figure 1: Inter-temporal measurements in an environment presenting an axial symmetry with respect to the axis $Oz$. Acoustical measurements between the AUV and the beacon are made at times $t_1$, $t_2$, $t_3$. Measurements $y(t_1)$ and $y(t_2)$ are identical and can be compared whereas $y(t_3)$ cannot be self-interpreted. In this 2D situation, we can establish the following relation: $y(t_1) = y(t_2) \Rightarrow x(t_2) = \pm x(t_1)$.

We obtained interesting results in simulated cases. This work has been presented in some conferences and we submitted a paper about it. However, we plan to improve this research by applying the algorithms on real datasets provided by the iXBlue company.

**Future related paper:**

- **Robot localization in an unknown but symmetric environment**
  Simon Rohou, Luc Jaulin, Lyudmila Mihaylova, Fabrice Le Bars, Sandor M. Veres

## 3.2 Dealing with time-uncertainties

The localization problem with the help of symmetry properties can be seen as a starting point of a research based on **inter-temporal measurements**. We understand this kind of information is underexploited in the field of robotics. New localization methods can be established with this approach. Before going further, we need to introduce new academic tools adapted to handle inter-temporal measurements and time-uncertainties. This leads us to the consideration of temporal functions.

A temporal function $f(t)$ maps time values $t$ to outputs $y$. In a guaranteed computation context, outputs are bounded and can be represented with intervals: $y \in [y]$. Hence, the considered function becomes *thick*: $[f](t)$. When this function describes signals or trajectories, we speak about *tube*: a recent representation in the field of Interval Analysis [16, 5, 4, 2]. Its implementation is made of slices: $t \mapsto [y]$: the more uncertain a trajectory is, the thicker the tube containing it will be. When trajectory's estimation is improved, the tube needs to be contracted, thus becoming thinner. Such a contraction is trivial when considering an infinite number of scalar inputs $t$ over tube's domain. However, the computed representation of tubes obliges us considering some discretization leading to the use of thick slices: $[t] \mapsto [y]$. Tube's contraction has to be done in this context without loosing solutions for the considered signal to represent. To our knowledge, there is no existing method performing this kind of contraction. We propose a *contractor* approach [6] applied on tubes to handle these thick slices, leading to time-uncertainties considerations. We are consequently able to deal with strong temporal uncertainties: this will be essential for future work described in Sections 5.1 and 5.2.

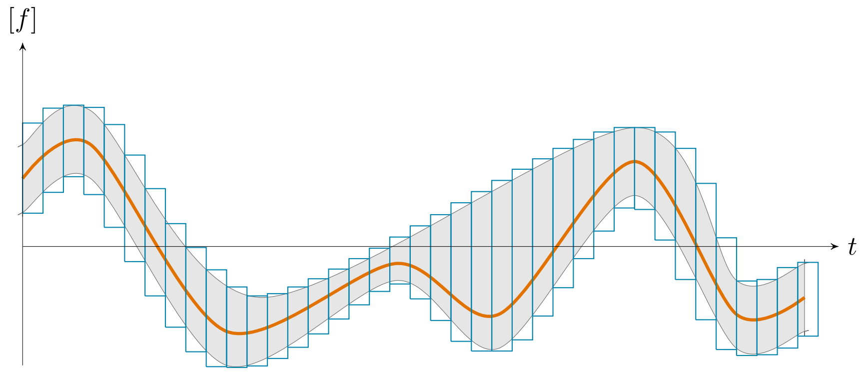


Figure 2: a *tube*: guaranteed representation of a set of trajectories (in light gray). A signal $s(\cdot)$ (in orange) belongs to an interval function so that: $\forall t, s(t) \in [f](t) = [f^-(t), f^+(t)]$. This ensures a guaranteed representation of signals. Functions $f^-(t)$ and $f^+(t)$ are represented with a set of boxes (in blue).

To this end, we implemented a new C++ library for tubes representations. Code is freely available on the GitHub software development platform:

**IBEX-Robotics library**
A complementary C++ library of IBEX for robotics purposes.
`https://github.com/ibex-team/ibex-robotics`

**Future related paper:**

- **Tube contractions applied to guaranteed non-linear state estimation with time-uncertainties**
  Simon Rohou, Luc Jaulin, Lyudmila Mihaylova, Fabrice Le Bars, Sandor M. Veres

### 3.3 Guaranteed integration

This research on tubes and their related tools – such as contractors, Section 3.2 – brings new ideas and enable us to consider the problem of guaranteed integration of differential equations [3, 19, 11, 8, 17, 12]. From an initial box $[\mathbf{x}](0)$, guaranteed integration [20] provides a set of techniques based on interval arithmetic to compute a box-valued function $[\mathbf{x}](t)$ (a *tube*) containing true values for the initial value problem. These methods provide interval counterparts of Euler [16], Runge-Kutta [7] or Taylor [18] integration and validate results using the Picard Theorem.

In robotics, guaranteed integration provides a reliable knowledge about robots trajectories. In this work, we propose a new approach based on tube arithmetic. Current experiments show interesting results when computing robot trajectories. This has been compared with existing methods, namely the CAPD DynSys library, well recognized in the community. Our approach is in fact particularly suitable for robots trajectories and seems to offer better results in this context. We have open discussions about this work during the SCAN'16 conference and the MRIS seminar about the Dependability of Complex Robotic Systems.

**Submitted paper:**

- **Guaranteed integration of robot trajectories**
  Simon Rohou, Luc Jaulin, Lyudmila Mihaylova, Fabrice Le Bars, Sandor M. Veres

## 4 Issues/Problems preventing from achieving PhD Targets

None, except time.

# 5 Future Research Activities

## 5.1 Localization based on loops and time-independent measurements

We are working on a new localization method based on loop closure detection [1].

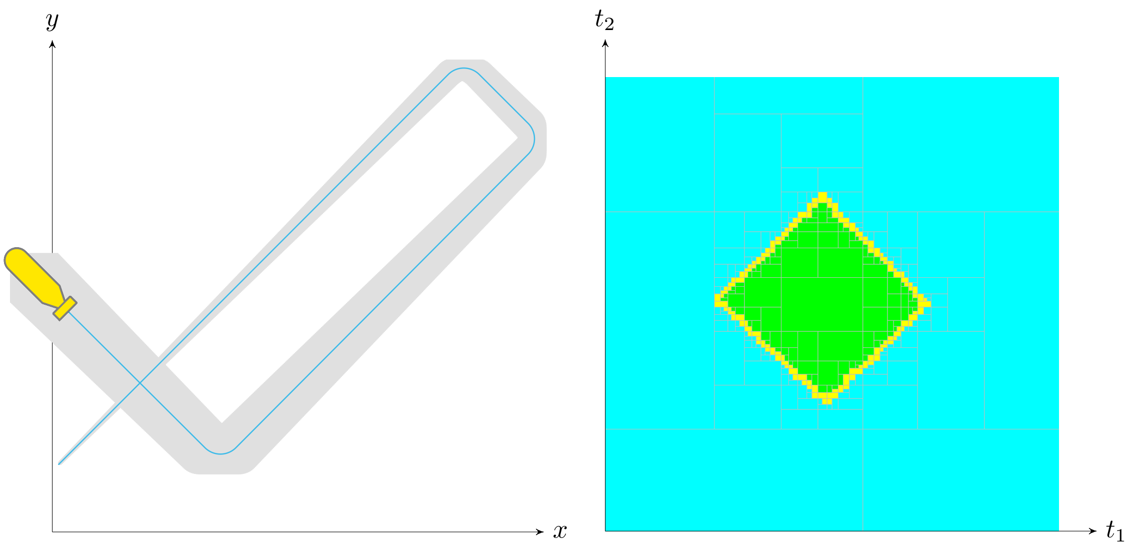


Figure 3: Guaranteed loop detection of a mobile robot [1]. A loop is described by a $t$-pair $(t_1, t_2)$ such that $\mathbf{p}(t_1) = \mathbf{p}(t_2)$ with $\mathbf{p}(t_1)$: the position of the robot at time $t_1$. Dealing with uncertainties, the computation of the solution results in a set represented in the $t$-plane by green and yellow boxes. This output can be used for state-estimation but the resulting boxes $[t_1]$, $[t_2]$ leads to time-uncertainties to handle – see Section 3.2

Figure 4: This new approach will be applied on datasets from Daurade AUV, with the kind help of *DGA Techniques Navales Brest*. To this end, a dedicated experiment has been made in October 2015: the AUV performed several loops in the Rade de Brest. Localization will be tried with bathymetric measurement. See first results in Fig. 5.

The idea is to combine the loop detection in robot's trajectory (based on its proprioceptive sensors) with some measurements. These measurements only need to be time-independent with respect to the duration of the mission. We can use many properties of the environment such as temperature, radioactivity, magnetism, luminosity, salinity, etc. Actually the more complex the environment is, the better our localization should be. For now, we plan to study scalar measurements.

To detect loops from proprioceptive measurements, we establish a $t$-plane (see Fig. 3). This way we obtain some sets (couples of times $t_1$, $t_2$) representing our loops where $\mathbf{p}(t_1) = \mathbf{p}(t_2)$. Here, $\mathbf{p}(t_1)$ is the position of the robot at time $t_1$. This approach has been studied in [1].

What we propose in this work is to contract these sets with the measurements $y(\cdot)$ so that : $y(t_1) \neq y(t_2) \Rightarrow p(t_1) \neq p(t_2)$. We plan to improve robot's localization around each loop (crossing trajectories). The improvement produced by the contraction is then propagated in forward-backward through the whole trajectory, thus improving robot's localization across the complete mission.

As far as we know, this approach is completely new: we propose a localization method that can work in a very poor environment where there is no land/sea marks and no visible object we can use to build a map. This is interesting for the *Explore and Return problem*, which remains one of the main topics in robotics. The SLAM method is one of the most famous to solve this problem and this work could be another concept.

We plan to demonstrate the relevance of this approach with real data from Daurade AUV, see Fig. 4.

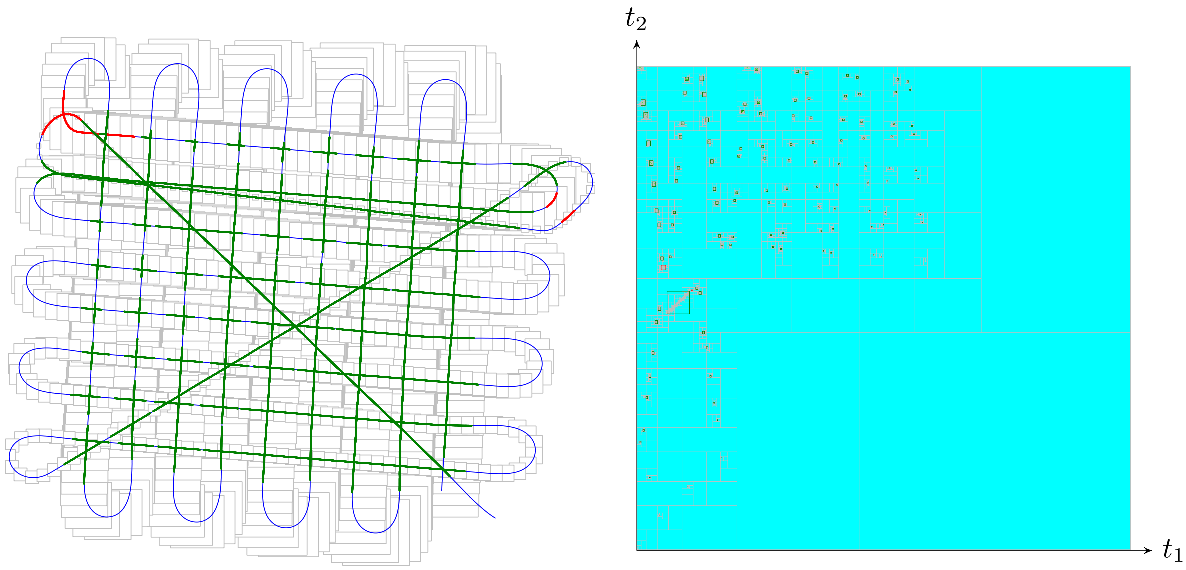


Figure 5: 2D trace of Daurade AUV and its corresponding $t$-plane – on the left hand side, gray rectangles are the bounded estimated positions – blue lines are the truth – green and red lines are the projection of the results given by a dedicated loop-detection test. On the right hand side, detected loops $(t_1, t_2)$ are represented inside a $t$-plane.

**Future related paper:**

- **Robot localization based on loops detections and time-independent scalar measurements**
  Simon Rohou, Luc Jaulin, Lyudmila Mihaylova, Fabrice Le Bars, Sandor M. Veres

## 5.2 Walking strategy

This part of the PhD is the initial subject (see Section 2.1 and Fig. 6). A bibliographic study revealed this subject has been dealt in the mean time by [14, 15] with real experiments. We still plan to work on this approach but considering additional constraints:

- low data rate communications (due to low-cost acoustical sensors)
- range-only measurements (due to low-cost acoustical sensors, too)
- low-cost platforms meaning inaccurate proprioceptive sensors

This leads to strong uncertainties, non-linear problems and needs of communications optimizations. The use of interval analysis methods is relevant in this context.

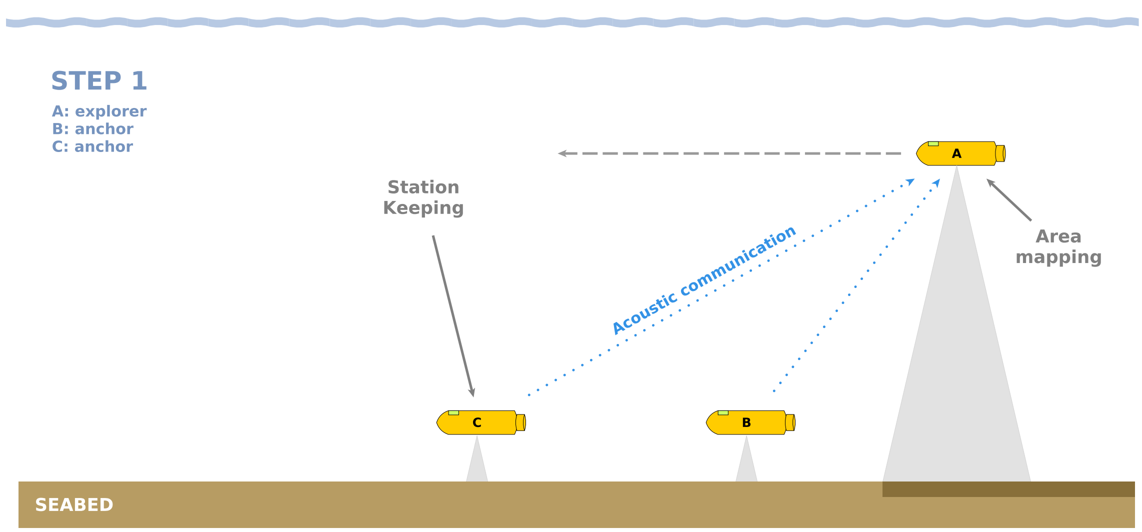


Figure 6: a Walking Technique with 3 AUVs: 1 explorer and 2 anchors

# 6 Communications, paper or publications

## 6.1 Talks

The following presentations have been made:

- [10/06/2015] **SWIM 2015** (Praha, Czech Republic)
  *Robot localization in an unknown but symmetric environment*
- [16/07/2015] **OSM Seminar** (Brest, France)
  *Robot localization in an unknown but symmetric environment*
- [09/03/2016] **GdR Robotique** (Montpellier, France)
  *Wide underwater area exploration with autonomous vehicles: a Walking Strategy*
- [24/06/2016] **PRASYS Seminar** (Brest, France)
  *Collaborative localization over the seabed: a Walking Strategy*
- [28/06/2016] **MRIS Seminar** (Brest, France)
  *Guaranteed computation of robots trajectories*
- [30/06/2016] **SHARC 2016** (Brest, France)
  *An overview of the MOOS-IvP middleware*
- [26-29/09/2016] **SCAN 2016** (Uppsala, Sweden)
  *Tube programming applied to state estimation*

Presentations are available here: `http://www.simon-rohou.fr/research/talks/`

## 6.2 Papers

We plan to publish the following papers before the end of the PhD:

1. **Guaranteed computation of robot trajectories** (submitted)
   Simon Rohou, Luc Jaulin, Lyudmila Mihaylova, Fabrice Le Bars, Sandor M. Veres
2. **Guaranteed non-linear state estimation with time-uncertainties**
   Simon Rohou, Luc Jaulin, Lyudmila Mihaylova, Fabrice Le Bars, Sandor M. Veres
3. **Robot localization based on loops detections and time-independent scalar measurements**
   Simon Rohou, Luc Jaulin, Lyudmila Mihaylova, Fabrice Le Bars, Sandor M. Veres
4. **Robot localization in an unknown but symmetric environment**
   Simon Rohou, Luc Jaulin, Lyudmila Mihaylova, Fabrice Le Bars, Sandor M. Veres
5. **Wide underwater area exploration with autonomous vehicles: a Walking Strategy**
   Simon Rohou, Luc Jaulin, Lyudmila Mihaylova, Fabrice Le Bars, Sandor M. Veres

## 6.3 Other

- I participated in *Forum DGA Innovation* (26/11/2015) with ENSTA Bretagne students and PhD students. We presented a real demonstration of a semi-autonomous boat equipped with viability algorithms for its own safety.
- I am in charge of MOOS-IvP courses at ENSTA Bretagne: a middleware for robotics purposes. See more: `http://simon-rohou.fr/cours/moos-ivp`
- I am in charge of the design of new autonomous robots: *Toutatis* AUVs and *Optical* AUVs, for research purposes: illustration of swarm algorithms, walking strategies, localization, etc.
- I participated in European robotics competitions SAUC-E and euRathlon (09/2014 and 09/2015) in Italy.

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