

Collaborative Localization over the Seabed: a Walking Strategy

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Section 1

Context



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Context

Motivations: exploration of a wide underwater area

Underwater exploration **without surfacing**:

- ▶ case of very deep environments (airplanes search)
- ▶ reasons of discretion and security (military mission)

Need for **localization methods** based on the following constraints:

- ▶ no underwater GNSS receiver
- ▶ unstructured environment: no landmark, complex SLAM

Current solution, **dead-reckoning**:

- ▶ navigation based on *proprioceptive* measurements
- ▶ fast drift on position estimation



Context

Walking strategy: an alternate landmark navigation

Proposition: use several **robots as landmarks**:

- ▶ smart behaviour leading to better localization
- ▶ global drift should be kept down

Two types of robots:

- ▶ **explorers**: robots performing the exploration, receiving signals
- ▶ **anchors**: robots laid on the seabed, emitting signals

Role of anchors and explorers will alternate during the mission.

Strategy of exploration called a **walking strategy**, where foot steps are performed by anchors.



Context

Walking strategy: an alternate landmark navigation

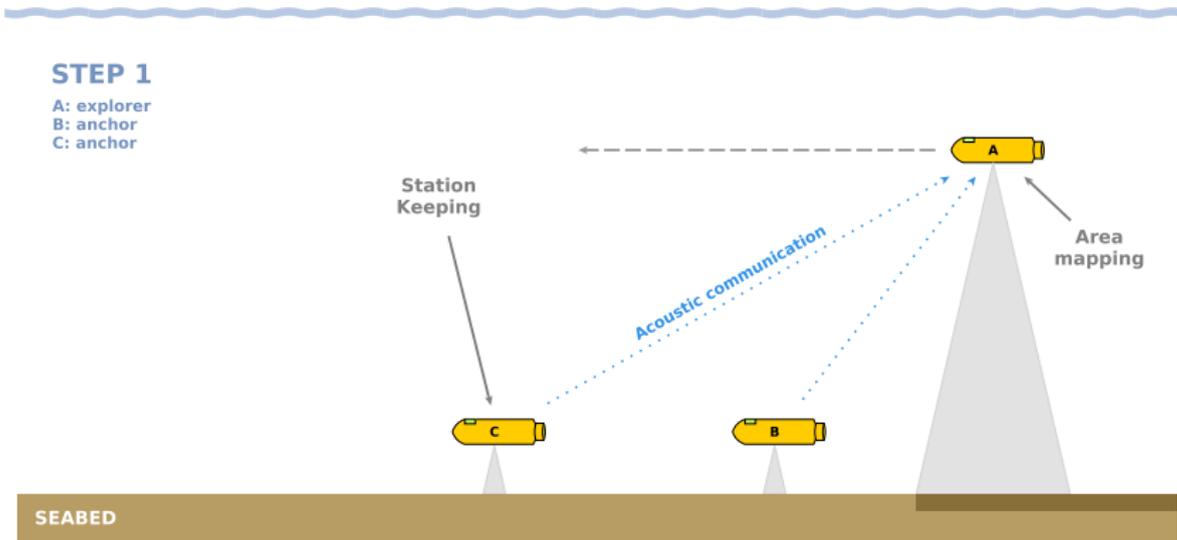


Figure: \mathcal{R}_A performing the exploration based on $d_{C \rightarrow A}$ and $d_{B \rightarrow A}$ ranges

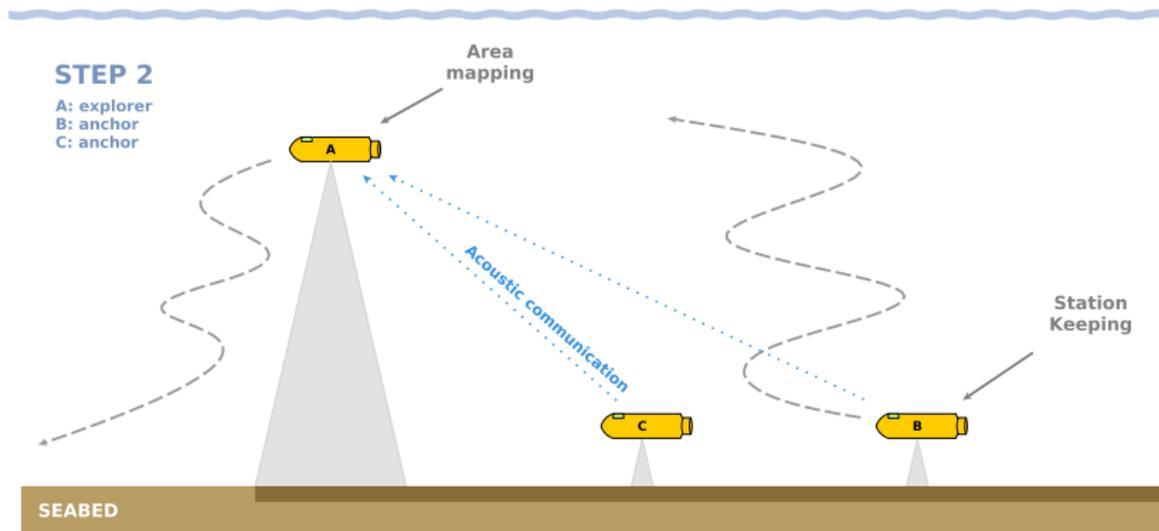


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Context

Walking strategy: an alternate landmark navigation

Figure: \mathcal{R}_A landing, \mathcal{R}_B preparing to exploreThe University
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Context

Walking strategy: an alternate landmark navigation

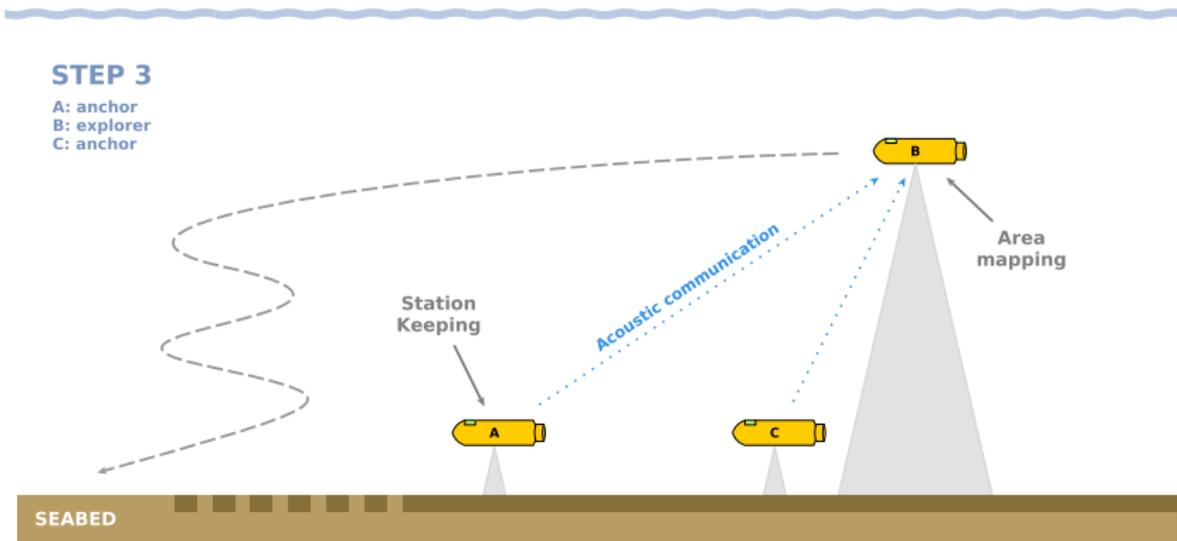


Figure: \mathcal{R}_B performing the exploration based on $d_{A \rightarrow B}$ and $d_{C \rightarrow B}$ ranges



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Context

Cost and underwater constraints

Underwater robotics:

- ▶ acoustics \implies low-data-rate communications
- ▶ low-cost acoustics sensors \implies range-only measurements
- ▶ low-cost platforms \implies inaccurate proprioceptive sensors

Consequences, needs to:

- ▶ optimize communications
- ▶ perform **range-only** inter-localization
- ▶ deal with **uncertainties**



Figure: low-cost
acoustical modem
(Micron Tritech)

Section 2

Formalization



Formalization System

Considering \bar{n} robots. A robot \mathcal{R}_j is described by:

$$\mathcal{R}_j \begin{cases} \dot{\mathbf{x}}^j &= \mathbf{f}(\mathbf{x}^j, \mathbf{u}^j) + b_{drift} \\ y^{j,l} &= d(\mathbf{x}^j, \mathbf{x}^l), l \neq j \end{cases} \quad (1)$$

- ▶ \mathbf{x}^j is the state vector of \mathcal{R}_j $\mathbf{x}^\top = \{x, y, z, \theta, v\}$
- ▶ \mathbf{u}^j is the input vector of \mathcal{R}_j $\mathbf{u}^\top = \{\dot{\theta}, \dot{v}\}$
- ▶ $y^{j,l}$ is a measurement between robots \mathcal{R}_j and \mathcal{R}_l
- ▶ $\mathbf{f} : \mathbb{R}^m \times \mathbb{R}^p \rightarrow \mathbb{R}^m$ is the *evolution* function
- ▶ $d : \mathbb{R}^m \times \mathbb{R}^m \rightarrow \mathbb{R}$ is a *distance* function
- ▶ b_{drift} is a noise

\mathcal{R}_j is an anchor $\iff b_{drift} = 0, \dot{\mathbf{x}} = \mathbf{0}, \mathbf{u} = \mathbf{0}$

Formalization

Range only localization

Observation function used for range-only data:

$$y^{j,l} = d(\mathbf{x}^j, \mathbf{x}^l) = \sqrt{(\mathbf{x}_1^j - \mathbf{x}_1^l)^2 + \dots}, \quad l \neq j \quad (2)$$

- ▶ state estimation \implies **non-linear problem**
- ▶ uncertainties can be handled with a set-membership approach

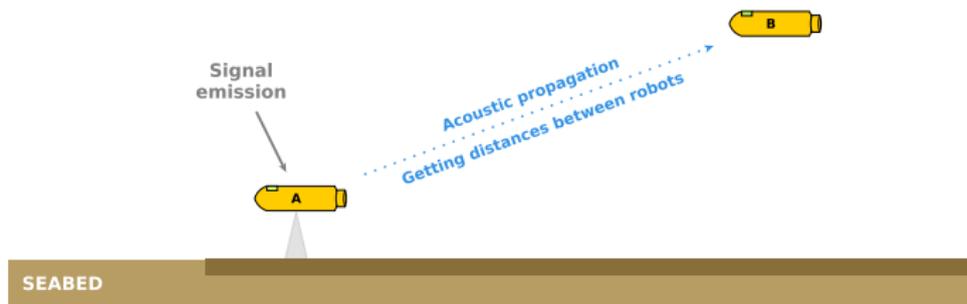


Figure: range-only localization from acoustical beacon



Section 3

Resolution with an interval method



Resolution with an interval method

Interval Analysis

An interval $[x]$:

- ▶ a closed and connected subset of \mathbb{R} delimited by two bounds
- ▶ $[x^-, x^+] = \{x \in \mathbb{R} \mid x^- \leq x \leq x^+\}$
- ▶ $[x] \in \mathbb{IR}$

A box $[\mathbf{x}]$:

- ▶ a cartesian product of n intervals
- ▶ $[\mathbf{x}] \in \mathbb{IR}^n$

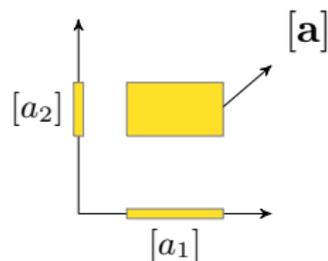


Figure: a box $[\mathbf{a}] \in \mathbb{IR}^2$

Resolution with an interval method

Interval Analysis

Interval analysis based on the extension of all classical real arithmetic operators:

- ▶ $+$, $-$, \times , \div
- ▶ ex: $[x] + [y] = [x^- + y^-, x^+ + y^+]$
- ▶ ex: $[x] - [y] = [x^- - y^+, x^+ - y^-]$

Adaptation of elementary functions such as:

- ▶ *cos*, *exp*, *tan*, etc.
- ▶ output is the smallest interval containing all the images of all defined inputs through the function



Resolution with an interval method

Set-membership estimation

Robot \mathcal{R}_j 's system:

$$\mathcal{R}_j \begin{cases} \dot{\mathbf{x}}^j &= \mathbf{f}(\mathbf{x}^j, \mathbf{u}^j) + b_{drift} \\ y^{j,l} &= d(\mathbf{x}^j, \mathbf{x}^l), \quad l \neq j \end{cases}$$

Input and measurement given by sensors with known uncertainties ; initial state \mathbf{x}_0^j bounded:

$$\mathbf{u}^j \in [\mathbf{u}^j], \quad y^{j,l} \in [y^{j,l}], \quad \mathbf{x}_0^j \in [\mathbf{x}_0^j]$$

Consequently with interval arithmetic, other variables contained in intervals:

$$\mathbf{x}^j \in [\mathbf{x}^j], \quad \dot{\mathbf{x}}^j \in [\dot{\mathbf{x}}^j]$$

Real drift enclosed in $[b_{drift}]$.

\mathcal{R}_j is an anchor $\implies [b_{drift}] = [0], [\dot{\mathbf{x}}] = [\mathbf{0}], [\mathbf{u}] = [\mathbf{0}]$



Resolution with an interval method

Set-membership estimation

Robot \mathcal{R}_j 's system:

$$\mathcal{R}_j \begin{cases} \dot{\mathbf{x}}^j &= \mathbf{f}(\mathbf{x}^j, \mathbf{u}^j) + b_{drift} \\ y^{j,l} &= d(\mathbf{x}^j, \mathbf{x}^l), l \neq j \end{cases}$$

Intervals $[\mathbf{x}]$, $[\dot{\mathbf{x}}]$, $[\mathbf{u}]$, $[y]$ evolve with time:

\implies representation within **tubes**



Resolution with an interval method

Tubes: definition

Tube $[x](t)$: interval of functions $[x^-, x^+]$ such that $\forall t \in \mathbb{R}, x^-(t) \leq x^+(t)$

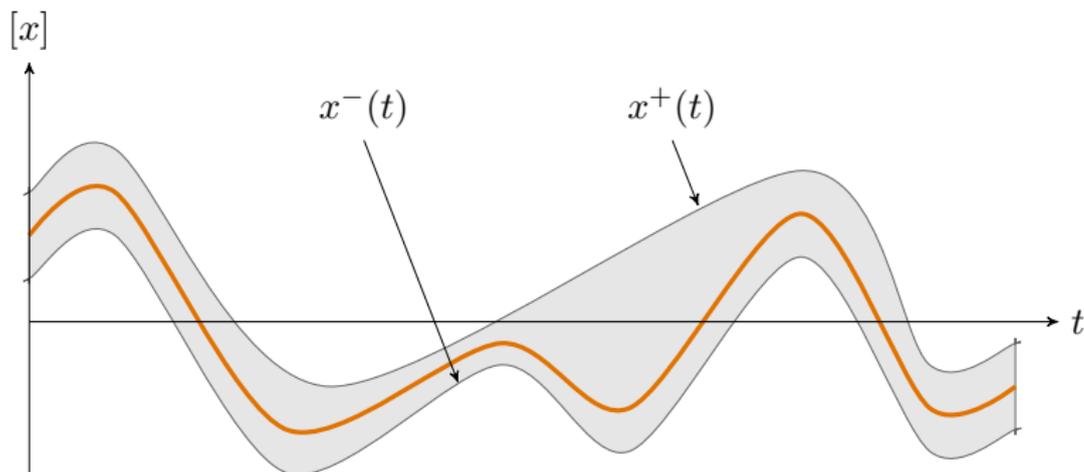


Figure: tube $[x](\cdot)$ enclosing true values $x^*(\cdot)$



Resolution with an interval method

Tubes: implementation

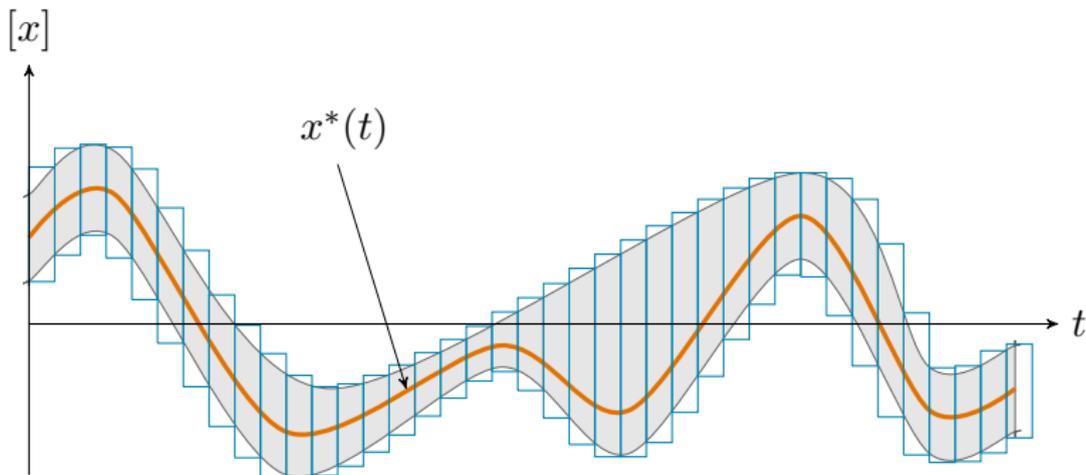


Figure: tube implementation with a set of boxes



IBEX-Robotics library

<https://github.com/ibex-team/ibex-robotics>



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Resolution with an interval method

Tubes: contractors

Contractor based on the observation $[y_1]$ made at time $[t_1]$.

$$[\mathbf{x}](t) = [\mathbf{x}](t) \cap \left([y_1] + \int_{t_1^-}^t [\dot{\mathbf{x}}](\tau) d\tau \right), \quad t \in [t_1^-, t_1^+]$$

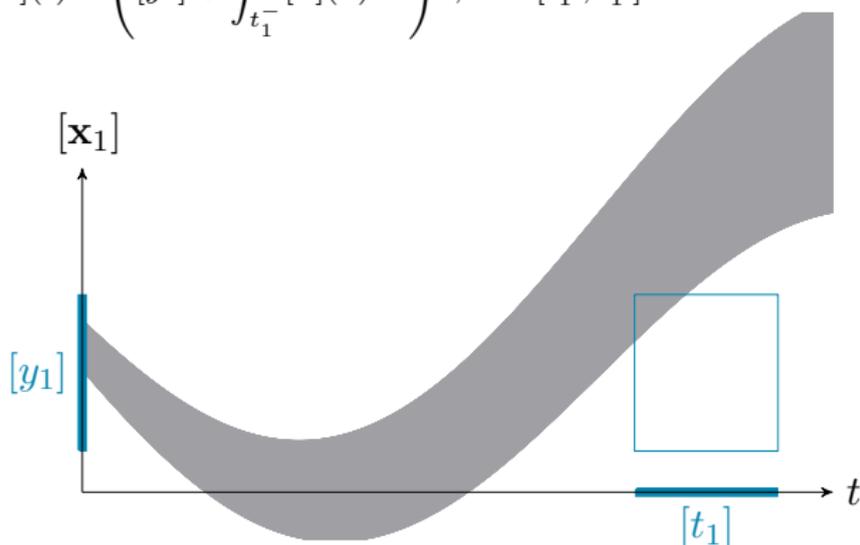


Figure: tube $[\mathbf{x}_1](t)$ before contraction



Resolution with an interval method

Tubes: contractors

Contractor based on the observation $[y_1]$ made at time $[t_1]$.

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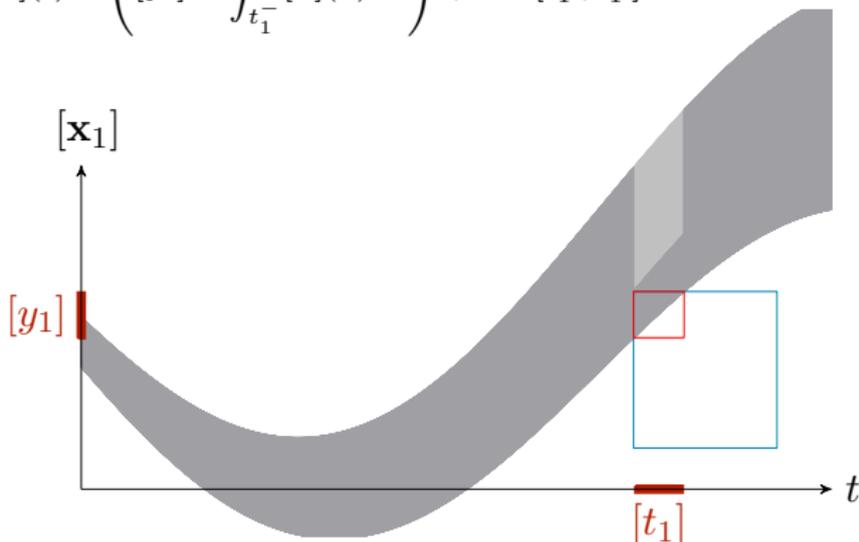


Figure: contraction of tube $[\mathbf{x}_1](t)$ and both $[y_1]$ and $[t_1]$

Resolution with an interval method

Tubes: contractors

Contractor based on the observation $[y_1]$ made at time $[t_1]$.

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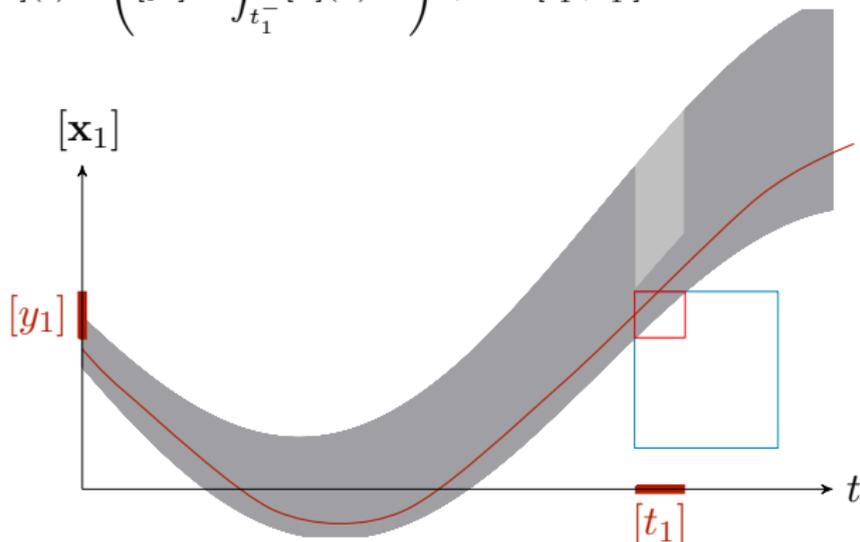


Figure: contraction of tube $[\mathbf{x}_1](t)$ and both $[y_1]$ and $[t_1]$

Resolution with an interval method

Tubes: contractors

Contractor based on the evolution function: $[\dot{\mathbf{x}}] = \mathbf{f}([\mathbf{x}], [\mathbf{u}])$

$$[\mathbf{x}](k) = [\mathbf{x}](k) \cap \left([\mathbf{x}](k-1) + \int_0^{\delta t} [\dot{\mathbf{x}}](k) d\tau \right)$$

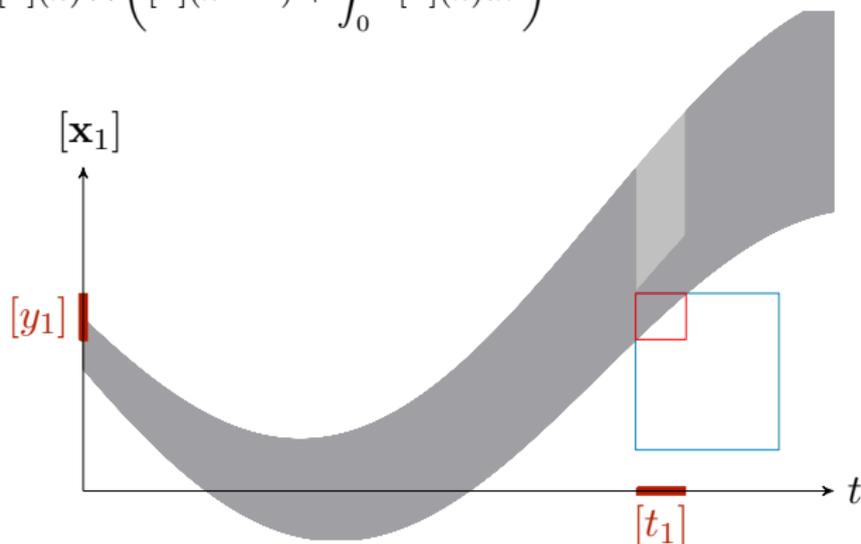


Figure: contraction of tube $[\mathbf{x}_1^j](t)$ and both $[y_1]$ and $[t_1]$

Resolution with an interval method

Tubes: contractors

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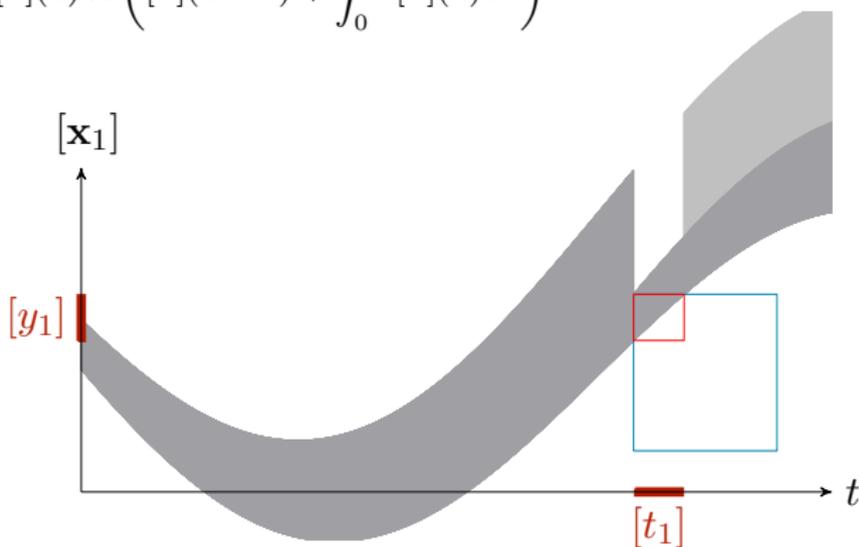


Figure: tube contraction in forward



Resolution with an interval method

Tubes: contractors

Contractor based on the evolution function: $[\dot{\mathbf{x}}] = \mathbf{f}([\mathbf{x}], [\mathbf{u}])$

$$[\mathbf{x}](k) = [\mathbf{x}](k+1) - \int_0^{\delta t} [\dot{\mathbf{x}}](k) d\tau$$

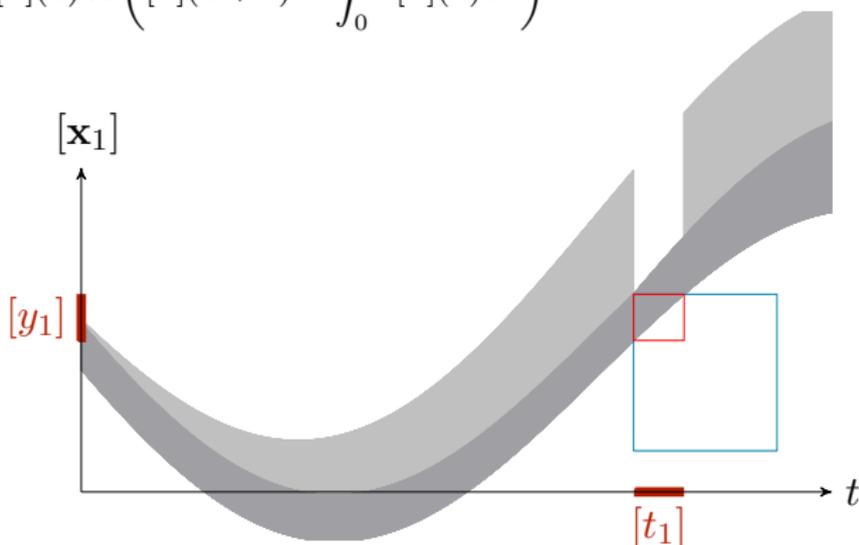


Figure: tube contraction in forward/backward



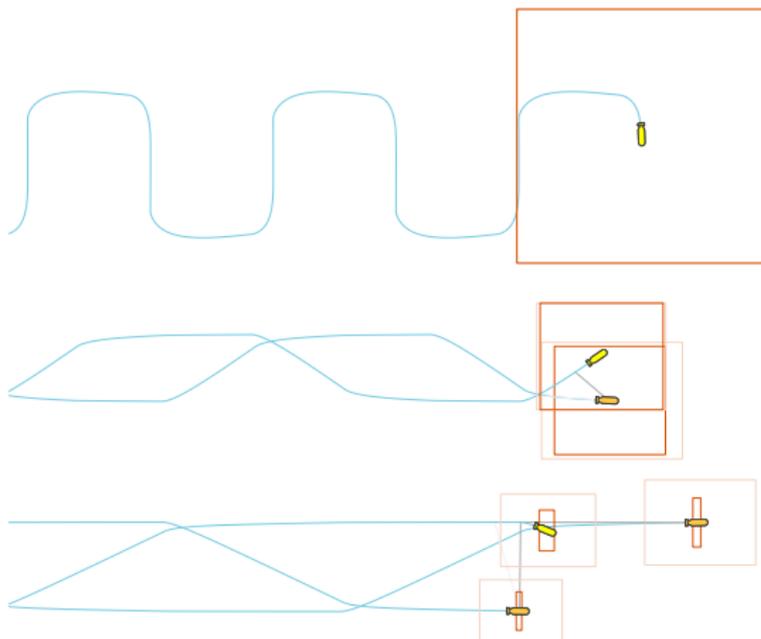
Section 4

Simulations



Simulations

Simulations: 1 AUV, 2 AUVs, 3 AUVs

Figure: **video:** walk of AUVs
[!\[\]\(befdcdf329f4bc1566e8bd49d7971740_img.jpg\) See on Youtube](#)

Simulations

Simulations: 1 AUV, 2 AUVs, 3 AUVs

Results obtained with identical robots and same covered area:

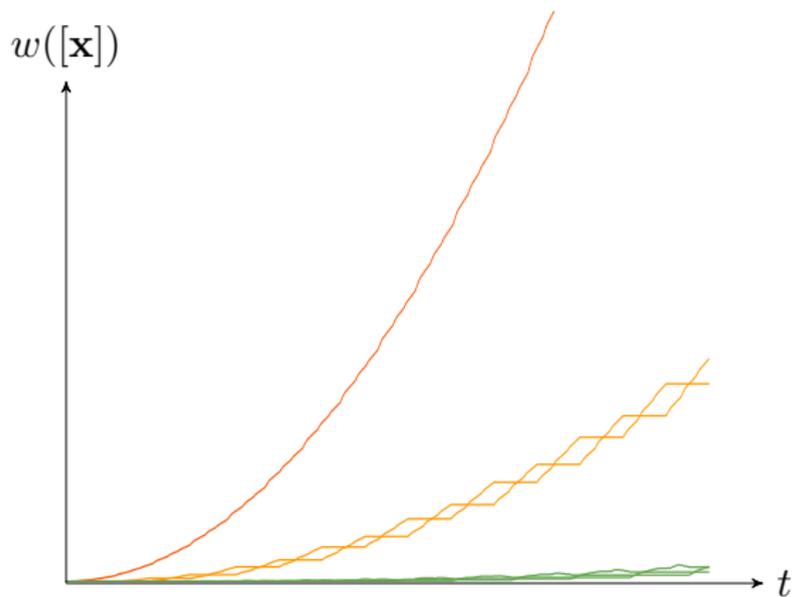


Figure: Considering the drift, represented by the width of each tube's slices. In red: 1 AUV dead-reckoning (quadratic drift), in orange: walk of 2 AUVs, in green: walk of 3 AUVs

Simulations

Loop trajectories

AUVs localization improved with a global loop trajectory:

- ▶ **sacrificed robot** \mathcal{R}_0 at start-point
- ▶ mission evolution
- ▶ come-back of robots near \mathcal{R}_0
- ▶ improvement of past-positions easily handled with tubes and backward contractors



Simulations

Simulations: loop trajectory with sacrificed robot

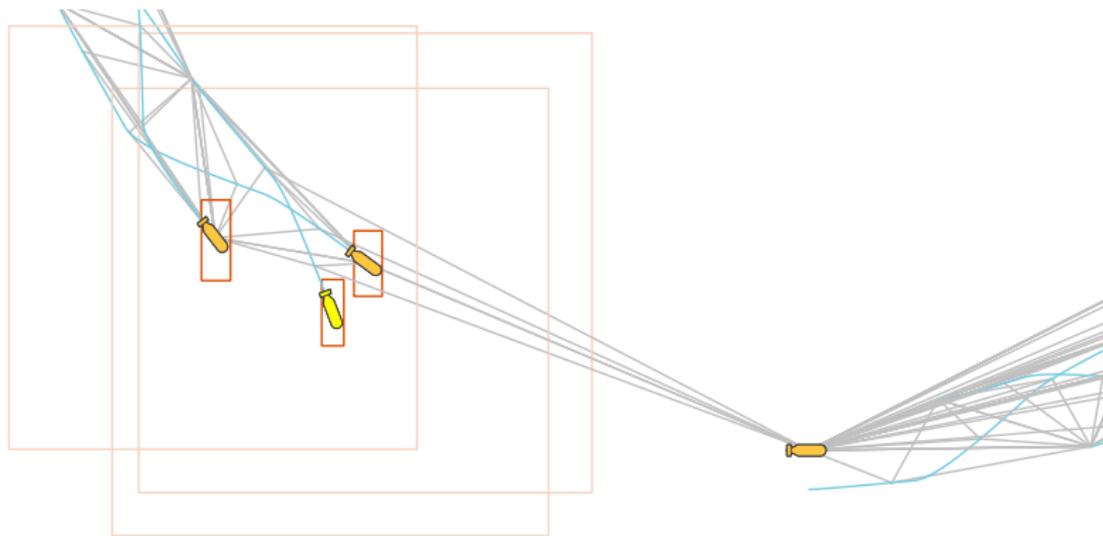


Figure: **video**: sacrificed robot on the right



See on Youtube



Section 5

Towards real experimentation



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Toutatis AUVs: Team of Organized Underwater robots for Autonomous Tasks of Inspection and Survey

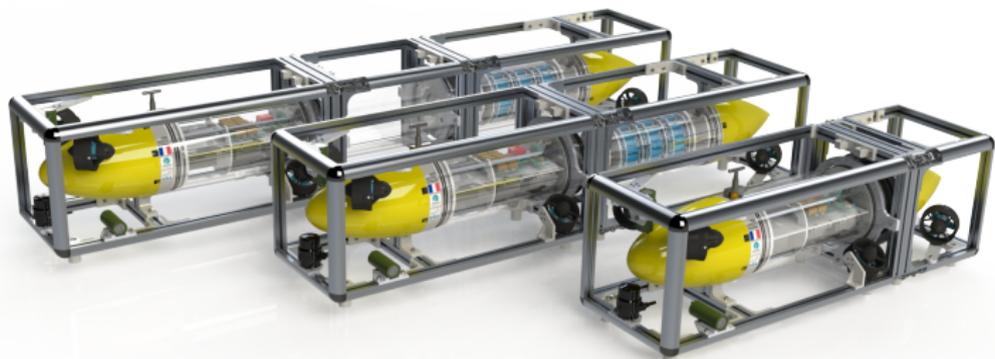


Figure: future Toutatis AUV's design

Conclusion

Use of interval analysis methods in this context:

- ▶ **non-linearities** easily handled
- ▶ guaranteed drift estimation with **bounded uncertainties**
- ▶ **low-rate** communication (only a few boxes communicated)



Conclusion

- ▶ several robots stronger than only one
- ▶ problems can be solved more easily with smart strategies
- ▶ more robots does not necessarily means more expensive

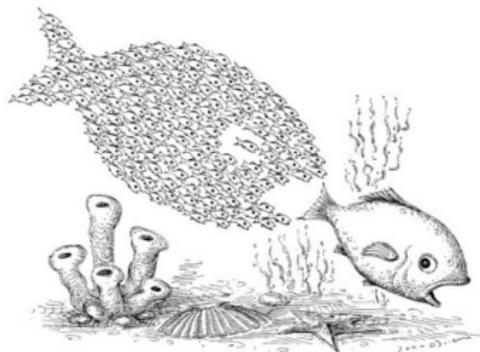


Figure: unity creates strength

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Support:



DGA

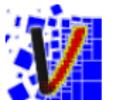
Direction Générale de l'Armement

Tools:



IBEX library

used for interval arithmetic, contractor programming



VIBES

used for rendering



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Section 8

Appendix



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Appendix

Acoustical communication from anchors to explorers:

- ▶ data-communication
 - ▶ message at landing (1 by footstep)
 - ▶ low rate \implies only anchor's box is broadcasted
 - ▶ message example: $([2.35, 4.92], [76.21, 84.36])$

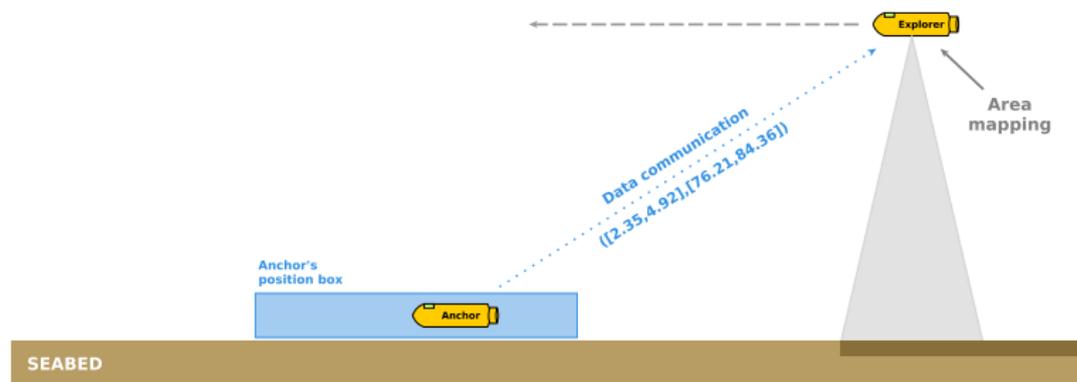


Figure: anchor broadcasting its position box



Appendix

Acoustical communication from anchors to explorers:

- ▶ data-communication
 - ▶ message at landing (1 by footstep)
 - ▶ low rate \implies only anchor's box is broadcasted
 - ▶ message example: $([2.35, 4.92], [76.21, 84.36])$
- ▶ range-only measurements

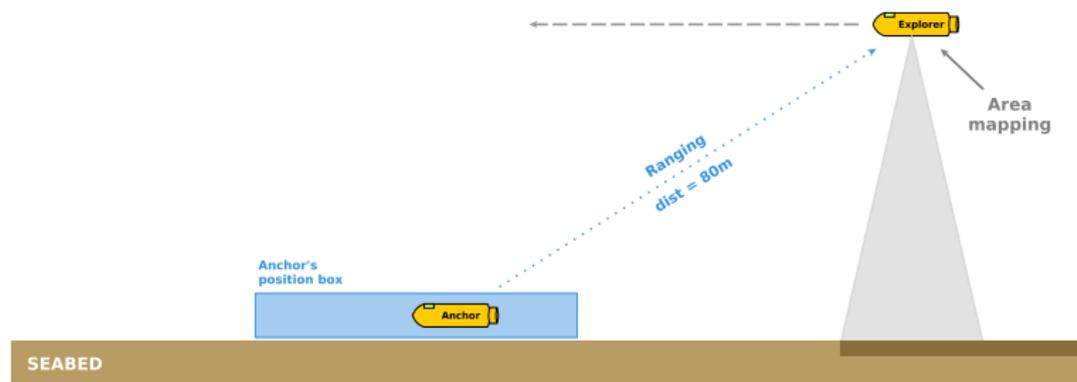
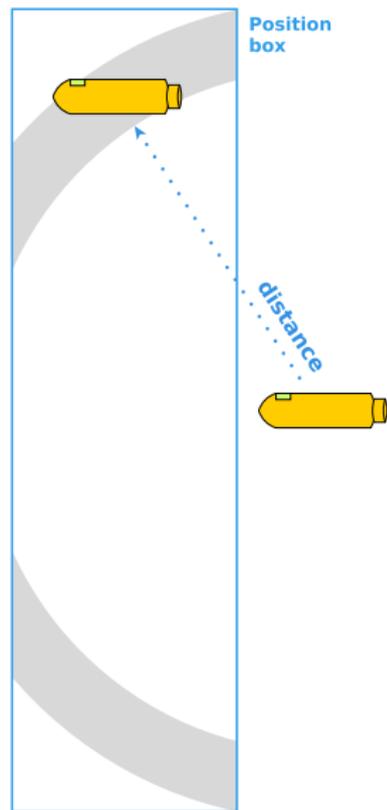


Figure: ranging between explorer and anchor



Appendix

Dealing with singularities

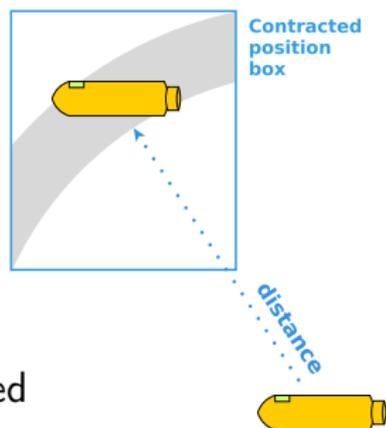


Appendix

Dealing with singularities

Solution: position-space **bisection**:

- ▶ use of a SIVIA algorithm
- ▶ one box bisected into two smaller boxes
- ▶ each box tested and bisected again if needed

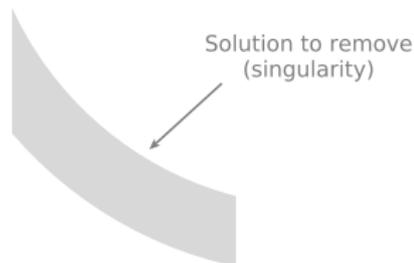


Smart trajectories can be found to remove singularities.



This example on YouTube

<https://youtu.be/aaqnKmKOUnY>



Appendix

Simulations: 1 AUV, 2 AUVs, 3 AUVs

3 AUVs group: one robot's tube:

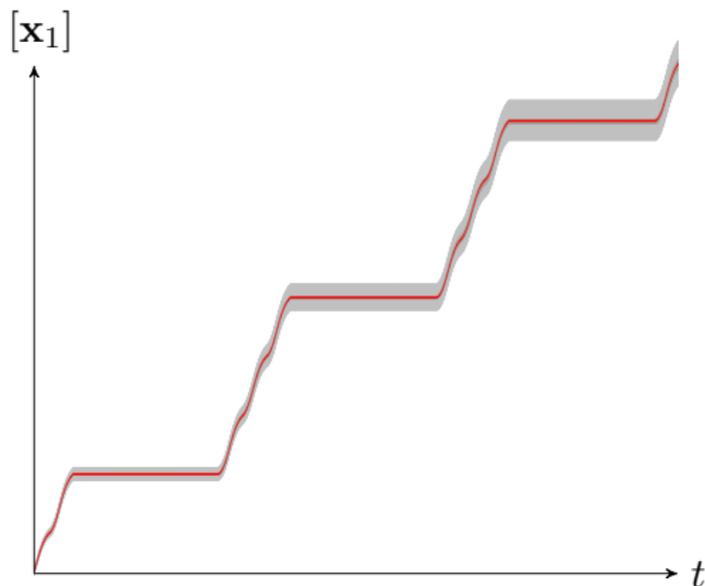


Figure: one contracted tube from 3 AUVs simulation



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Appendix

Simulations: 1 AUV, 2 AUVs, 3 AUVs

3 AUVs group: one robot's tube:

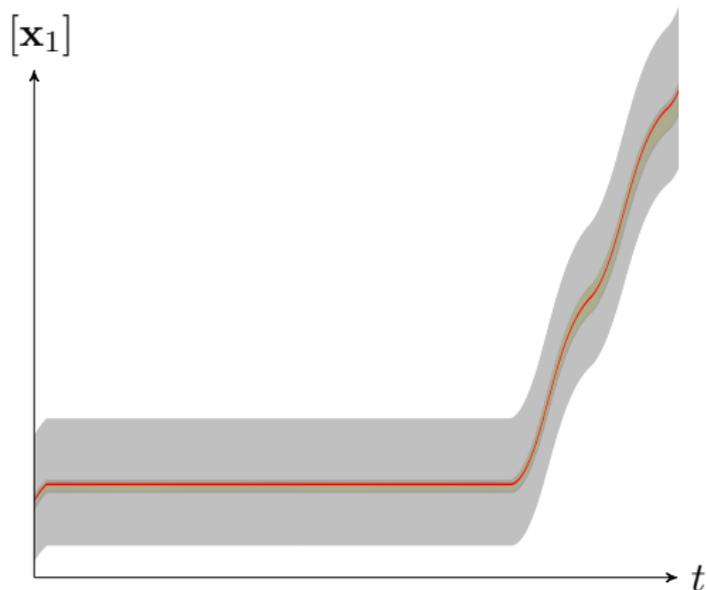


Figure: one contracted tube from 3 AUVs simulation (zoom)