Wide Underwater Area Exploration with Autonomous Vehicles: a Walking Strategy

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Section 1

Context

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

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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

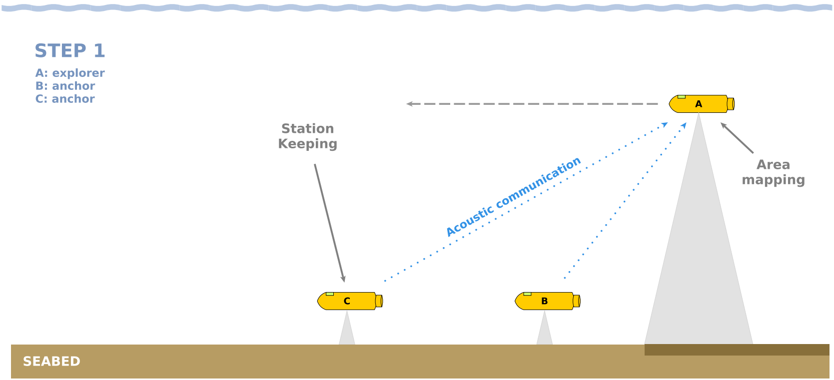

Figure: $\mathcal{R}_A$ performing the exploration based on $d_{C\to A}$ and $d_{B\to A}$ ranges

Context

Walking strategy: an alternate landmark navigation

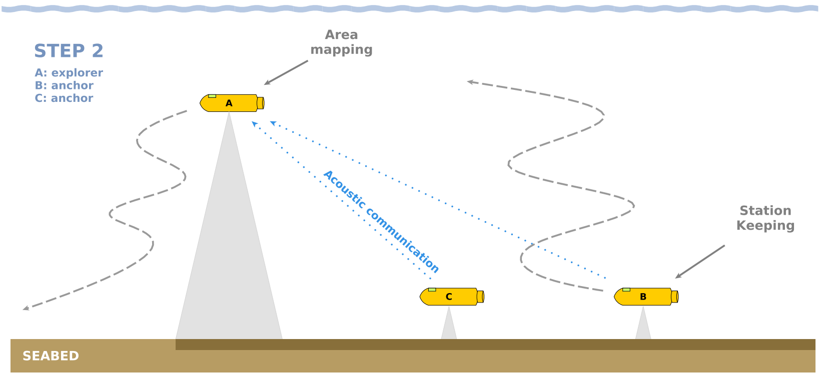

Figure: $\mathcal{R}_A$ landing, $\mathcal{R}_B$ preparing to explore

Context

Walking strategy: an alternate landmark navigation

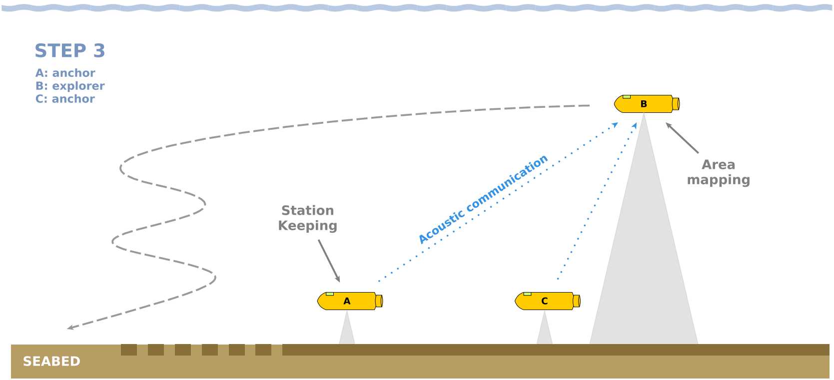

Figure: $\mathcal{R}_B$ performing the exploration based on $d_{A\rightarrow B}$ and $d_{C\rightarrow B}$ ranges

Context

Cost and underwater constraints

Underwater robotics:

- acoustics $\Longrightarrow$ low-data-rate communications
- low-cost acoustics sensors $\Longrightarrow$ range-only measurements
- low-cost platforms $\Longrightarrow$ 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 $\overline{n}$ robots. A robot $\mathcal{R}_j$ is described by:

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

- $\mathbf{x}^j$ is the state vector of $\mathcal{R}_j$ $\quad \mathbf{x}^\intercal = \{x, y, z, \theta, v\}$
- $\mathbf{u}^j$ is the input vector of $\mathcal{R}_j$ $\quad \mathbf{u}^\intercal = \{\dot{\theta}, \dot{v}\}$
- $y^{j,l}$ 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 $\Longleftrightarrow b_{drift} = 0 \ , \ \dot{\mathbf{x}} = \mathbf{0} \ , \ \mathbf{u} = \mathbf{0}$

Formalization

Range only localization

Observation function used for range-only data:

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

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

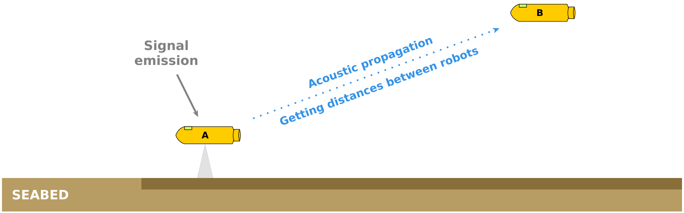

Figure: range-only localization from acoustical beacon

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
- $[x^-, x^+] = \{x \in \mathbb{R} \mid x^- \leqslant x \leqslant x^+\}$
- $[x] \in \mathbb{IR}$

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

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

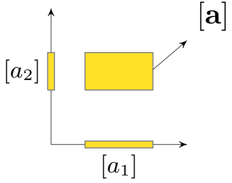

Figure: a box $[\mathbf{a}] \in \mathbb{IR}^2$

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:

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

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

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

Consequently with interval arithmetic,
other variables contained in intervals:

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

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:

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

$\Longrightarrow$ representation within **tubes**

Resolution with an interval method

Tubes: definition

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

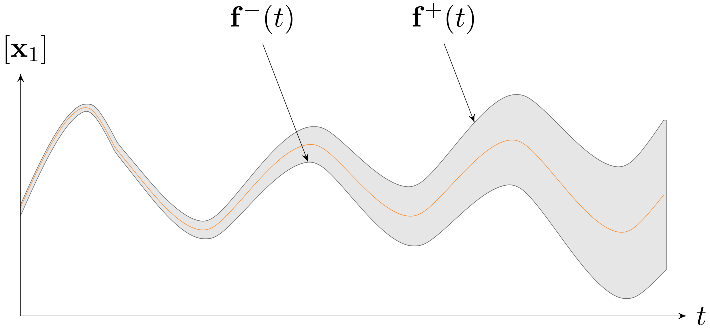

Figure: tube $[\mathbf{x}_1](t)$ enclosing true values (orange)

Resolution with an interval method

Tubes: contractors

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

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

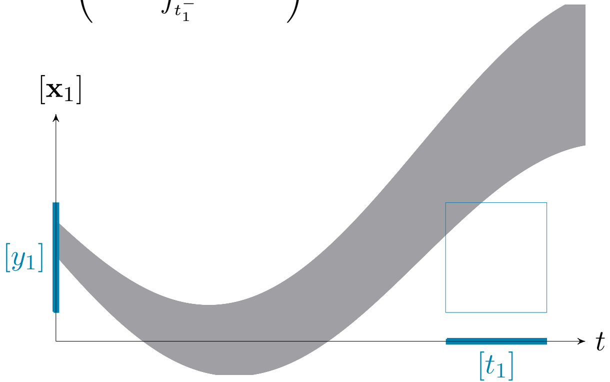

Figure: tube $[\mathbf{x}_1](t)$ before contraction

Resolution with an interval method

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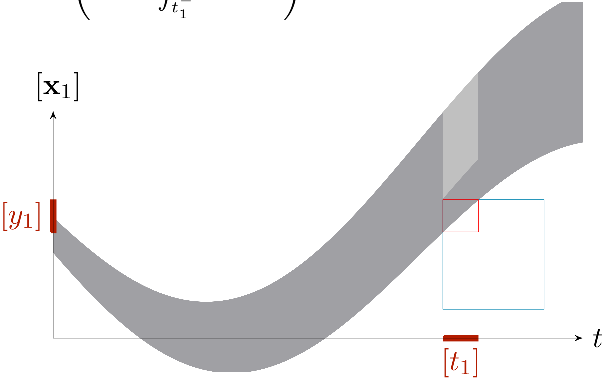

Figure: contraction of tube $[\mathbf{x}_1](t)$ and both $[y_1]$ and $[t_1]$

Resolution with an interval method

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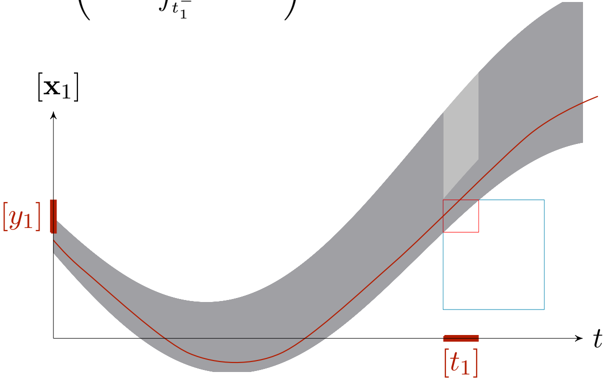

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Resolution with an interval method

Tubes: contractors

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

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

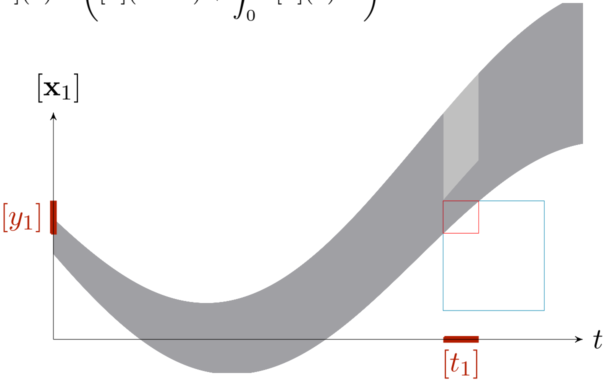

Figure: contraction of tube $[\mathbf{x}_1^j](t)$ and both $[y_1]$ and $[t_1]$

Resolution with an interval method

Tubes: contractors

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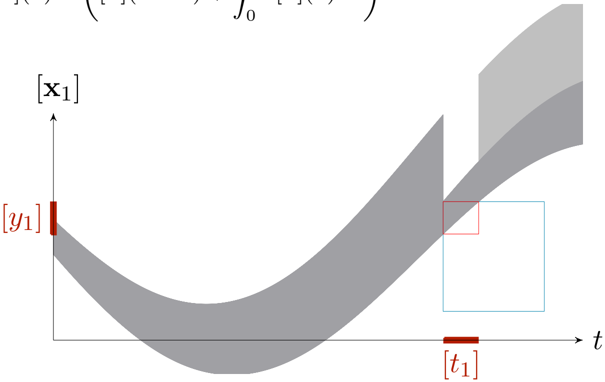

Figure: tube contraction in forward

Resolution with an interval method

Tubes: contractors

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

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

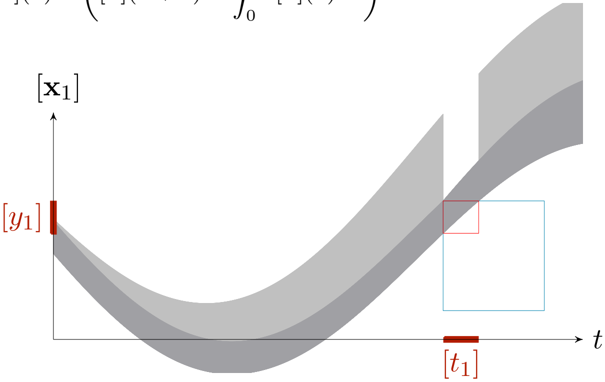

Figure: tube contraction in forward/backward

Section 4

Simulations

Simulations

Communication

Acoustical communication from anchors to explorers:

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

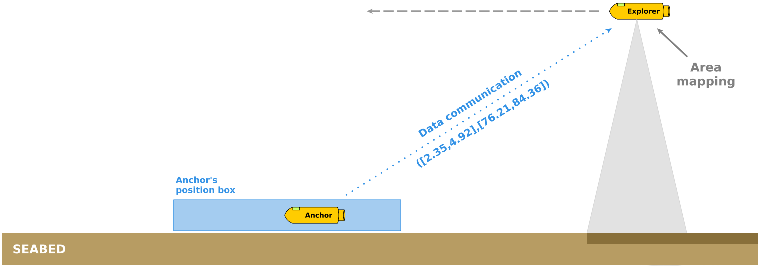

Figure: anchor broadcasting its position box

Simulations

Communication

Acoustical communication from anchors to explorers:

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

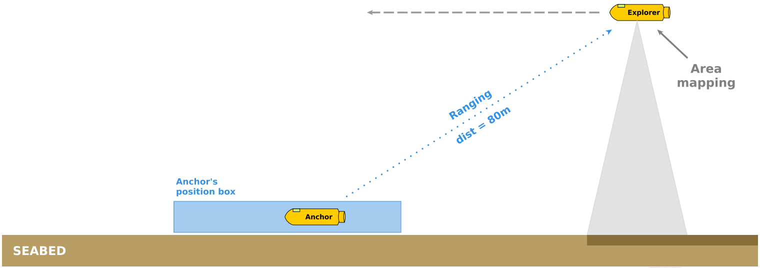

Figure: ranging between explorer and anchor

Simulations

Simulations: 1 AUV, 2 AUVs, 3 AUVs

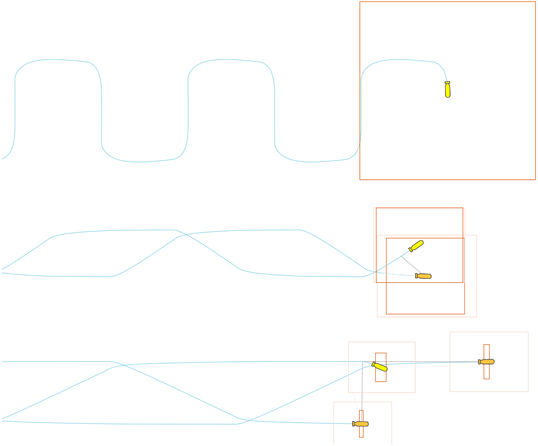

Figure: **video:** walk of AUVs

See on Youtube

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

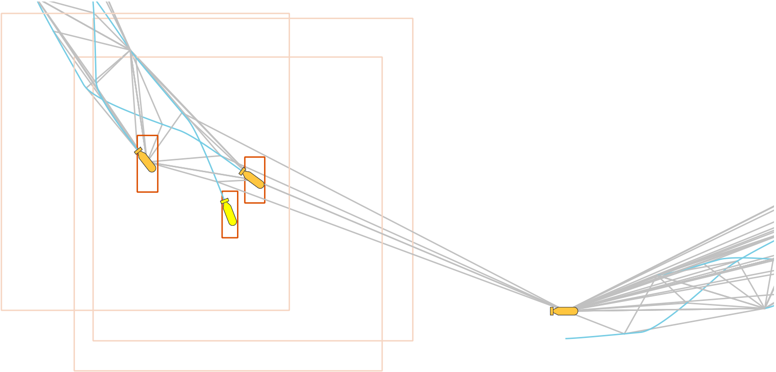

Figure: **video:** sacrificed robot on the right

See on Youtube

Section 5

Towards real experimentation

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

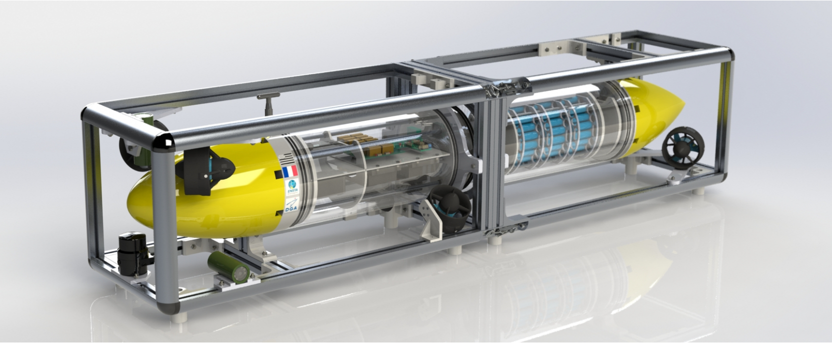

Figure: future Toutatis AUV's design

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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 necesarily means more expensive

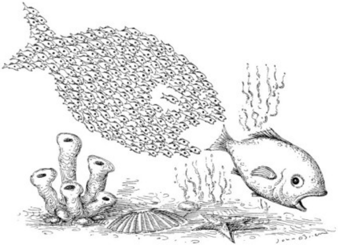

Figure: unity creates strength

Support:

DGA
Direction Générale de l'Armement

Tools:

IBEX library
used for interval arithmetic, contractor programming

VIBES
used for rendering

References:

[Matsuda15] T. Matsuda, T. Maki, Y. Sato, T. Sakamaki,
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[Chabert09] G. Chabert, L. Jaulin,
Contractor programming,
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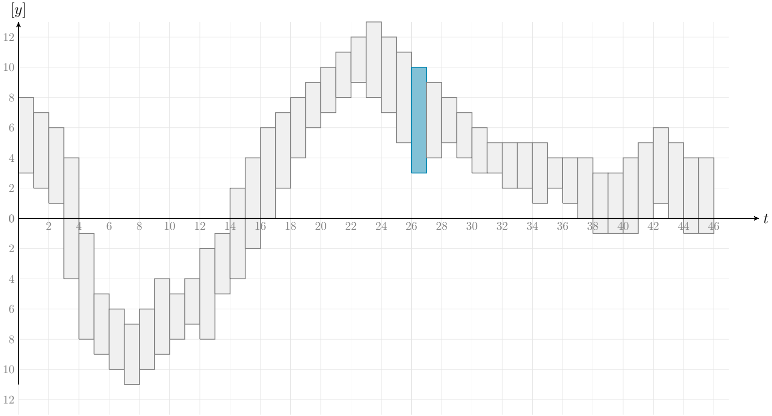
Robust interval-based localization algorithms for mobile sensor networks,
International Journal of Distributed Sensor Networks, 1-7, 2012.

Section 8

Appendix

Appendix

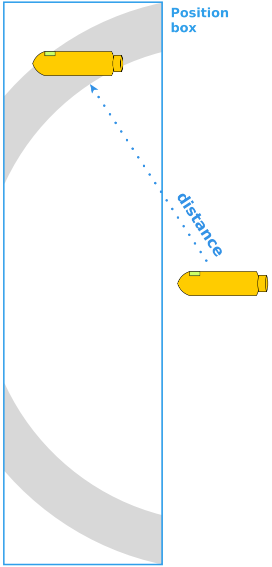
Tubes: implementation



IBEX-Robotics library
https://github.com/ibex-team/ibex-robotics

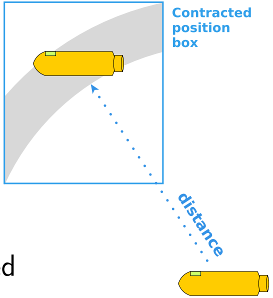
Appendix

Dealing with singularities



Appendix

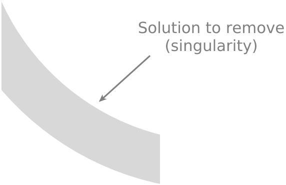
Dealing with singularities



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:

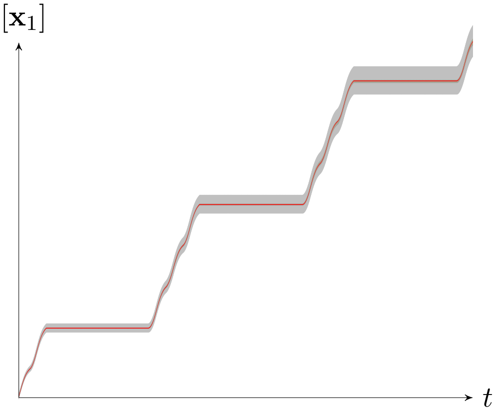


Figure: one contracted tube from 3 AUVs simulation

Appendix

Simulations: 1 AUV, 2 AUVs, 3 AUVs

3 AUVs group: one robot's tube:

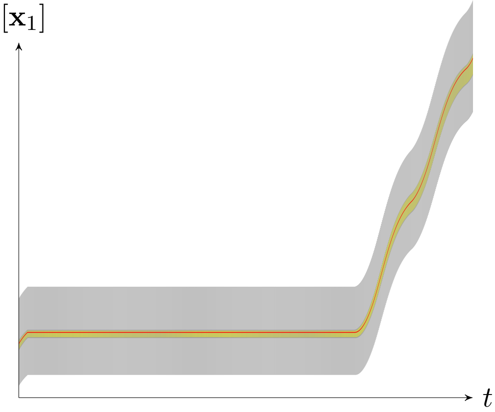


Figure: one contracted tube from 3 AUVs simulation (zoom)