Set membership approach for underwater exploration with swarms

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Organismes financeurs

Partenaires

Outline

1. Underwater exploration with swarms
2. Localization and explored area characterization
   - Localization
   - Explored area
   - Set-membership approach
3. Experimental results
   - AUV swarm simulation
   - Guaranteed explored area computation

Underwater exploration with swarms.

It is sometimes necessary to explore a given zone, and to ensure that it has been entirely covered (mapping, mine hunting, search, ...)

AUV swarms:

- robustness through redundancy and diversity
- scalability
- cooperation

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In this talk

- Localize the swarm of robots
- Characterize the explored area w.r.t localization uncertainty

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Localization.

- Surface : GPS
- Underwater :
  No installed infrastucture for localization.
  - Dead reckoning
  - Acoustical localization system

$$\begin{cases} \dot{\mathbf{x}}(t) &= \mathbf{f}(\mathbf{x}(t),\mathbf{u}(t)) \\ \mathbf{y}(t) &= \mathbf{g}(\mathbf{x}(t)) \end{cases}$$

- dead reckoning
- GPS, acoustic ranges

Use boxes (interval vectors) $[\mathbf{x}]$ and $[\mathbf{y}]$ to represent positions and measurements, and their uncertainties.

Inter-AUV communication for localization

- Time of arrival measurements -> ranges
- Emitter's position box is transmitted

Each communication is a constraint between two AUV positions.

- Communication enables contraction of position boxes
- Repeated contractions enhance swam localization

Outline

What area has been explored by the swarm?

$$\begin{cases} \dot{\mathbf{x}}(t) & = & \mathbf{f}\left(\mathbf{x}(t),\mathbf{u}(t)\right) \\ \mathbf{y}(t) & = & \mathbf{g}\left(\mathbf{x}(t)\right) \\ \mathbb{V}(t) & = & \left\{\mathbf{z}\in\mathbb{R}^2 : v\left(\mathbf{z},\mathbf{x}(t)\right)\leq 0\right\} \\ \mathbb{M} & = & \bigcup_{t\in[t]}\mathbb{V}(t) \end{cases}$$

- evolution
- observation
- visibility
- explored map

This formalism can represent the single AUV case as well as the full swarm:

- $\mathbf{x}$ is the state of the swam
- observations are GPS positions and inter-AUV range measurements.

Visible area and explored area

The visible area at time t is represented by the set-valued function $\mathbb{V}(t)$:

$$\mathbb{V}(t) = \{\mathbf{z} \in \mathbb{R}^2 : v(\mathbf{z}, \mathbf{x}(t)) \leq 0\}$$

where $v(\mathbf{z}, \mathbf{x}(t))$ is the visibility function.
Let $\mathbb{M}$ be the map of the explored area. $\mathbb{M}$ is the union of the visible areas over the whole trajectory:

$$\mathbb{M} = \bigcup_{t \in [t]} \mathbb{V}(t)$$

Bracketing of the visible area: guaranteed and possible

Guaranteed visible area $\mathbb{V}^{\forall}$: set of points that have necessarily been observed, regardless of the state uncertainty

$$\mathbb{V}^{\forall}(t) = \left\{\mathbf{z} \in \mathbb{R}^2 : \forall \mathbf{x}(t) \in [\mathbf{x}](t), v(\mathbf{z}, \mathbf{x}(t)) \leq 0\right\} \quad (1)$$

Possible visible area $\mathbb{V}^{\exists}$: set of points that may have been in the robot's field of view:

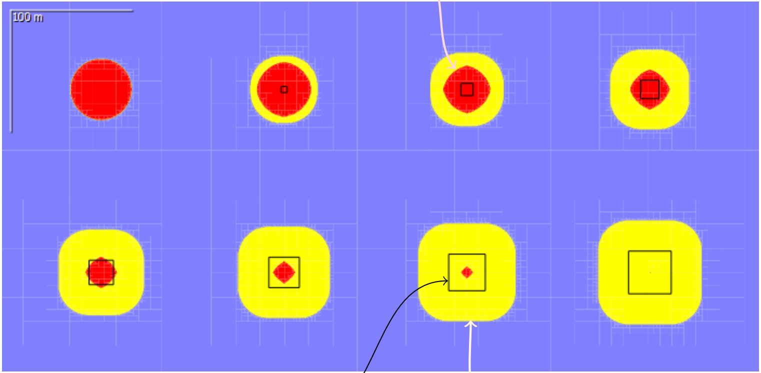
$$\mathbb{V}^{\exists}(t) = \left\{\mathbf{z} \in \mathbb{R}^2 : \exists \mathbf{x}(t) \in [\mathbf{x}](t), v(\mathbf{z}, \mathbf{x}(t)) \leq 0\right\} \quad (2)$$

$\mathbb{V}^{\forall}(t)$ and $\mathbb{V}^{\exists}(t)$ form a bracketing of the actual visible area $\mathbb{V}(t)$:

$$\forall t \in [t], \mathbb{V}^{\forall}(t) \subset \mathbb{V}(t) \subset \mathbb{V}^{\exists}(t)$$

Guaranteed visible area depends on position accuracy

Guaranteed visible area $\mathbb{V}^{\forall}$

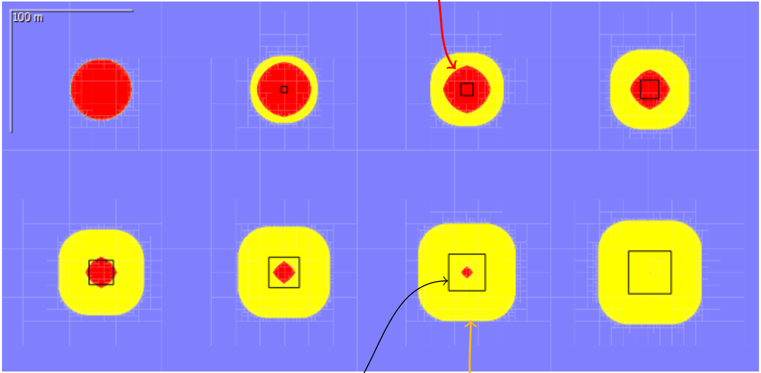


Position uncertainty box [x]

Possible visible area $\mathbb{V}^{\exists}$

Guaranteed visible area depends on position accuracy

Guaranteed visible area $\mathbb{V}^{\forall}$



Position uncertainty box $[\mathbf{x}]$

Possible visible area $\mathbb{V}^{\exists}$

Guaranteed and possible explored area

Guaranteed explored area $\mathbb{M}^{\forall}$: union of all the guaranteed visible areas during the mission

$$\mathbb{M}^{\forall} = \bigcup_{t \in [t]} \mathbb{V}^{\forall}(t), \tag{3}$$

Possible explored area $\mathbb{M}^{\exists}$: union of all the possible visible areas over time

$$\mathbb{M}^{\exists} = \bigcup_{t \in [t]} \mathbb{V}^{\exists}(t). \tag{4}$$

A bracketing of the actual explored area $\mathbb{M}$ is given by

$$\mathbb{M}^{\forall} \subset \mathbb{M} \subset \mathbb{M}^{\exists}.$$

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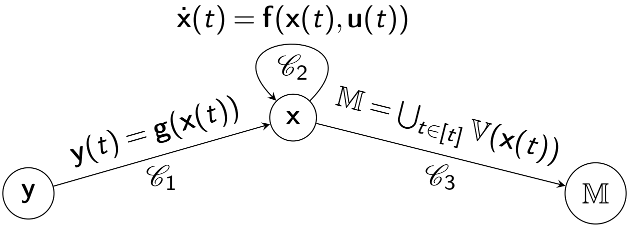
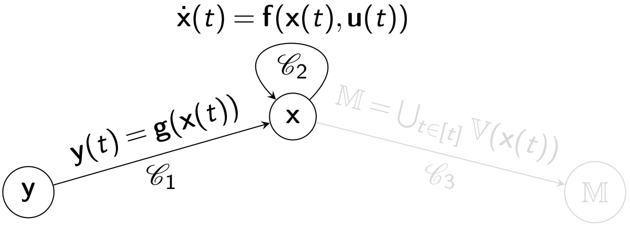
Constraint satisfaction problem



Variables: $\mathbf{x}$, $\mathbf{u}$, $\mathbf{y}$, $\mathbb{M}$.

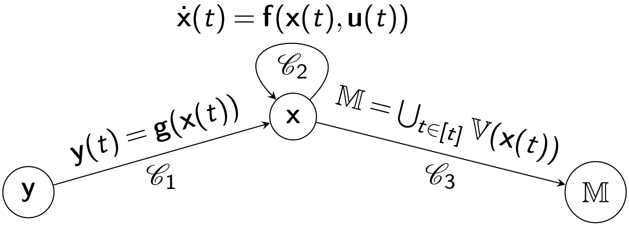
Domains: Tubes (function intervals) $[\mathbf{x}]$, $[\mathbf{y}]$ and $[\mathbf{u}]$. Set interval $[\mathbb{M}]$.

Contraction process



1. Contract the trajectory tube until a fixed point
   - observations
   - differential equation
2. Compute a bracketing of the map (union of SIVIA)

Contraction process



1. Contract the trajectory tube until a fixed point
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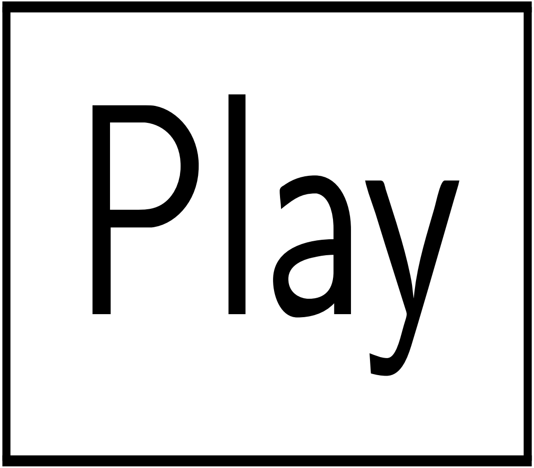
Outline

AUV swarm simulation.



Simulate a swarm of AUVs equipped with

- GPSs
- Speed and depth sensors
- INS
- Acoustical communication and ranging

Mission: exploration and sonar mapping of an 1.5 km x 2 km area

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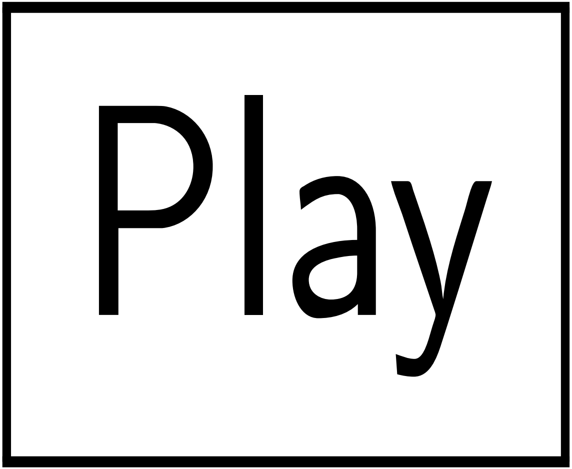
AUV swarm: exploration of an area.

Play

AUV localization uncertainty.



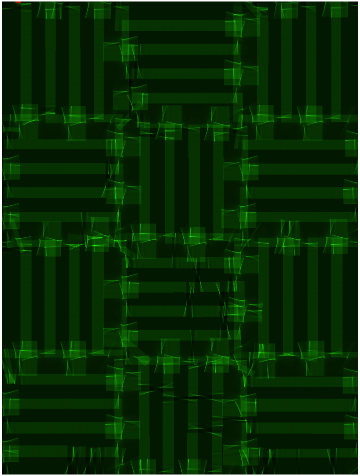
- Boxes represent position uncertainty
- Control done wrt box centers
- Range measurements contract boxes

AUV swarm simulation

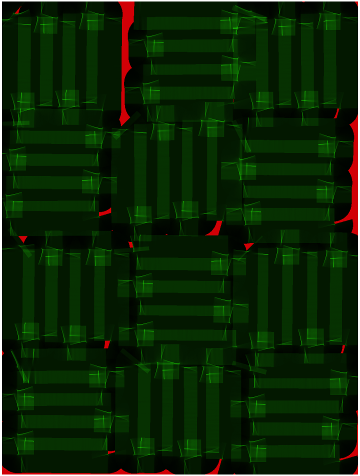
Communication improves accuracy and coverage.

Red=unexplored. Green intensity=number of scans

- With communication



- Without communication



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Position refining.

Before contraction

- Constraint propagation with distance measurements
- Forward-backward constraint propagation over trajectory with evolution equation

Position refining.

Contraction...

- Constraint propagation with distance measurements
- Forward-backward constraint propagation over trajectory with evolution equation

Position refining.

Contraction...

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Position refining.

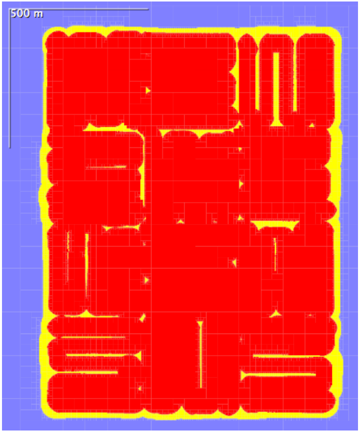
After contraction

- Constraint propagation with distance measurements
- Forward-backward constraint propagation over trajectory with evolution equation

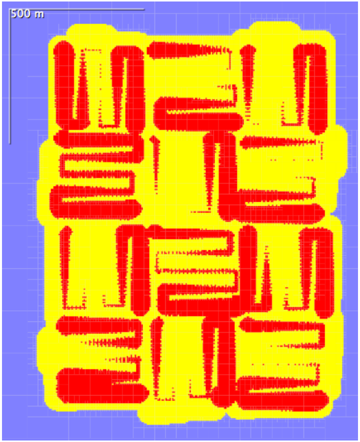
Explored area computation.

Red=guaranteed ($\mathbb{M}^{\forall}$), Yellow=possible ($\mathbb{M}^{\exists}$)

- With communication



- Without communication



Summary

- Set membership approach for localization of AUVs in a swarm
- Guaranteed bracketing of the explored area
- Inter-AUV communication and ranging improves exploration coverage, and validation

- Outlook
  - Tighten the explored area set interval.
  - Deal with erroneous measurements and prevent rumour propagation in the swarm.
  - Swarm of different robots