3D Path Planning of a Communication and Navigation Aid Vehicle for Multiple AUV Operations

6th Biannual NRC-IOT Workshop on Underwater Vehicle Technology

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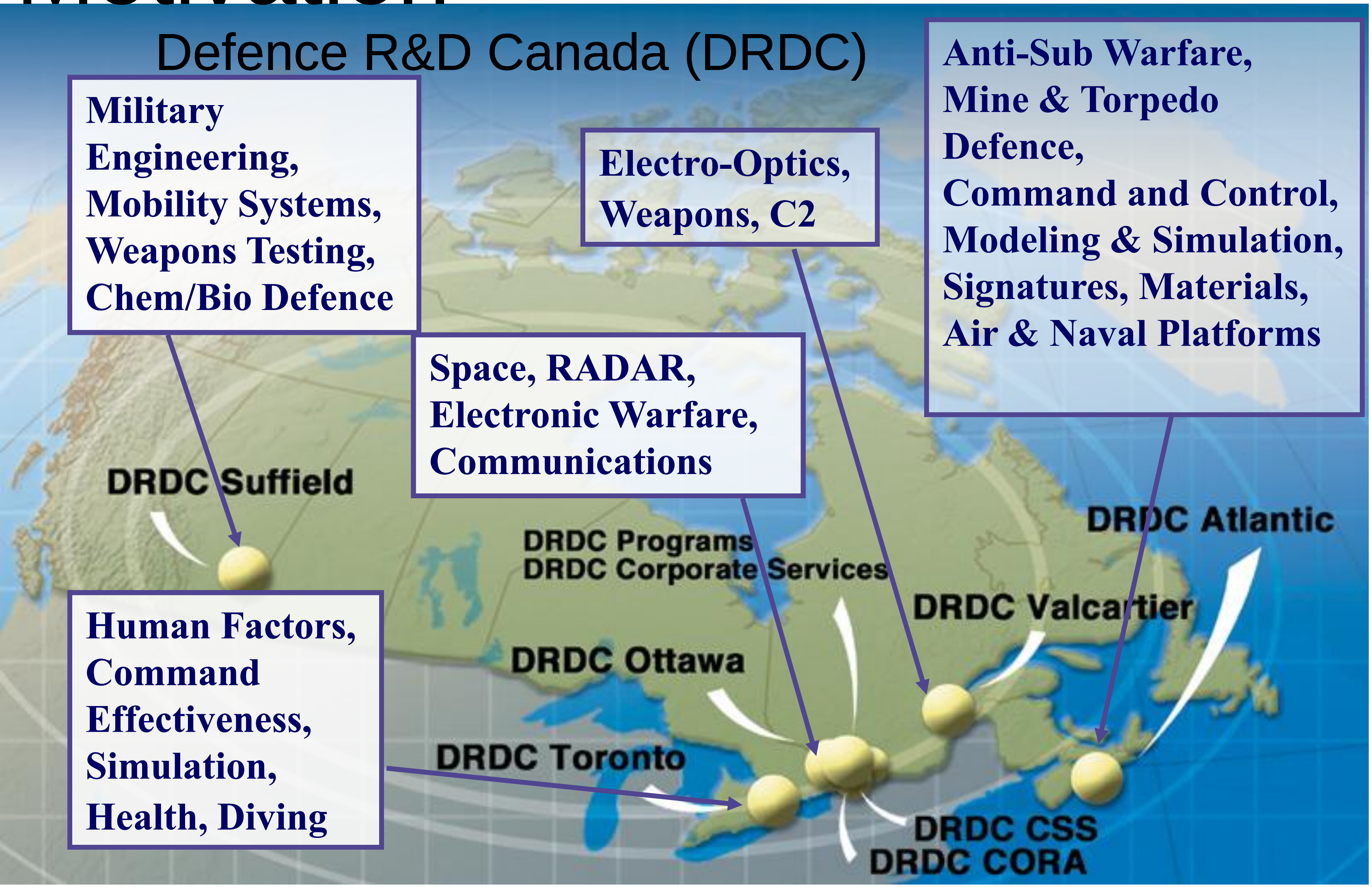
Presentation Outline

1. Typical Side Scan Sonar Survey Patterns
2. Communication and Navigation Limitations in AUV Operations
3. Communication and Navigation Aid (CNA) Concept
4. Path Planning for CNA Vehicle – 2D & 3D
5. Progress
6. Future Work
7. Conclusion

Motivation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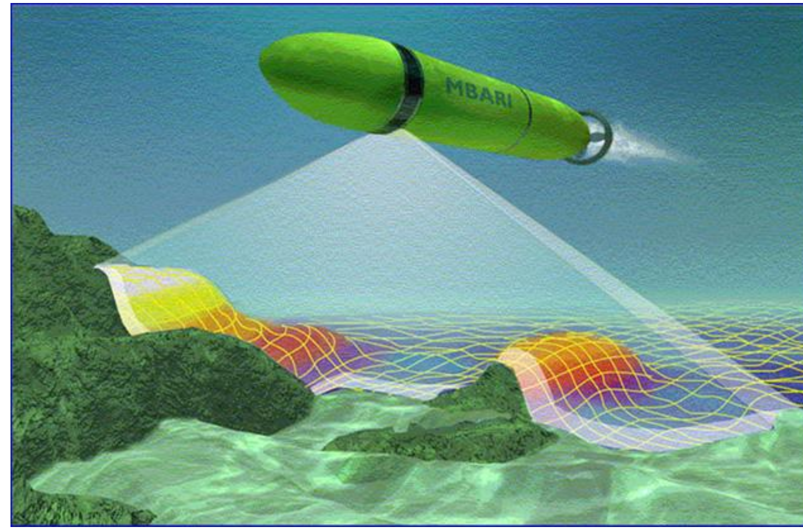
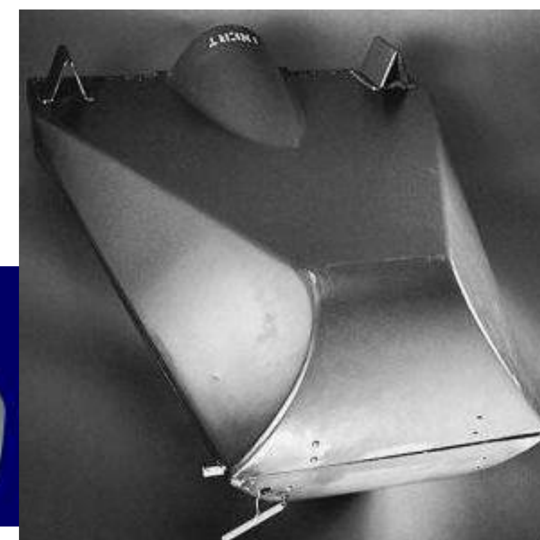
Motivation



AUV at Work – Monterey Bay Aquarium Research Institute

- Mine: manufactured, underwater explosive device designed to damage or destroy ships or submarines.
- Rather than moored mines, the mines of primary interest here are (generally small) seabed mines in up to 100m of water.
- Mines located with side scan sonar.

Rockan mine



Jane's Underwater Warfare Systems

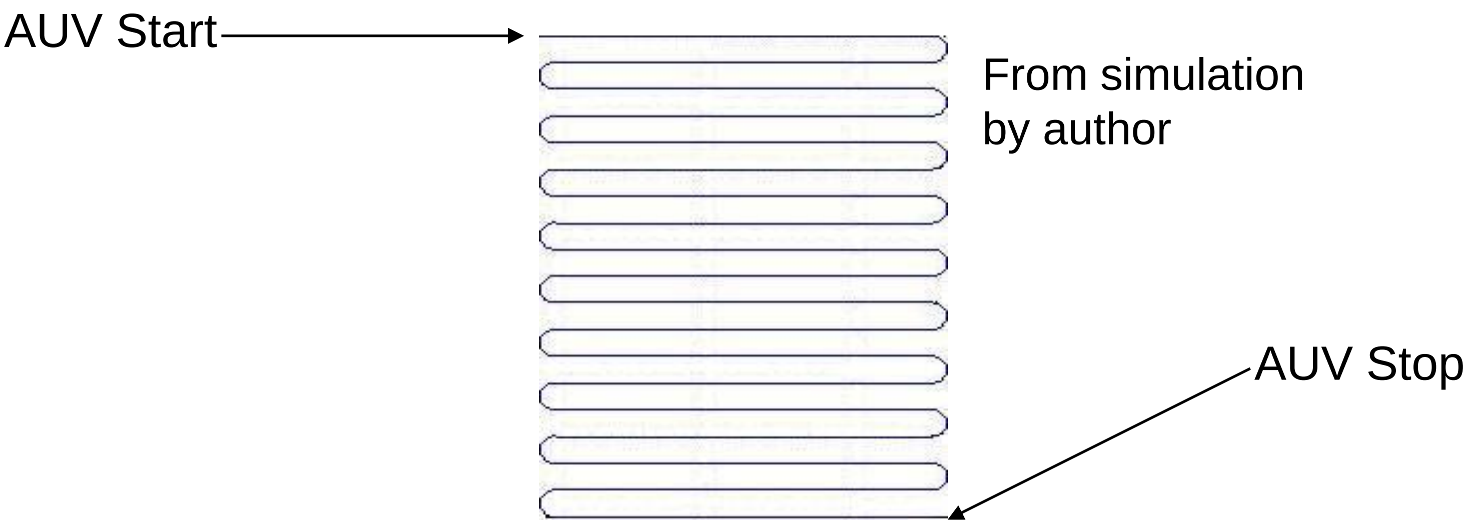
Manta mine

Murena mine

http://www.sei-spa.com

Single AUV Survey

Common minehunting mission for a single minehunting AUV (Autonomous Underwater Vehicle) with sidescan sonar: lawnmower / ladder pattern

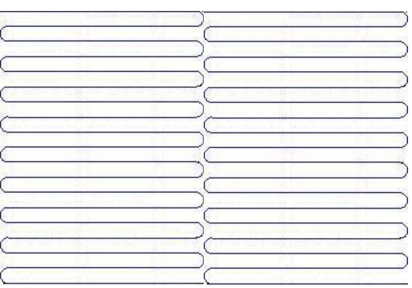


From simulation by author

Multi-AUV Survey

Area may simply be divided among available AUVs.

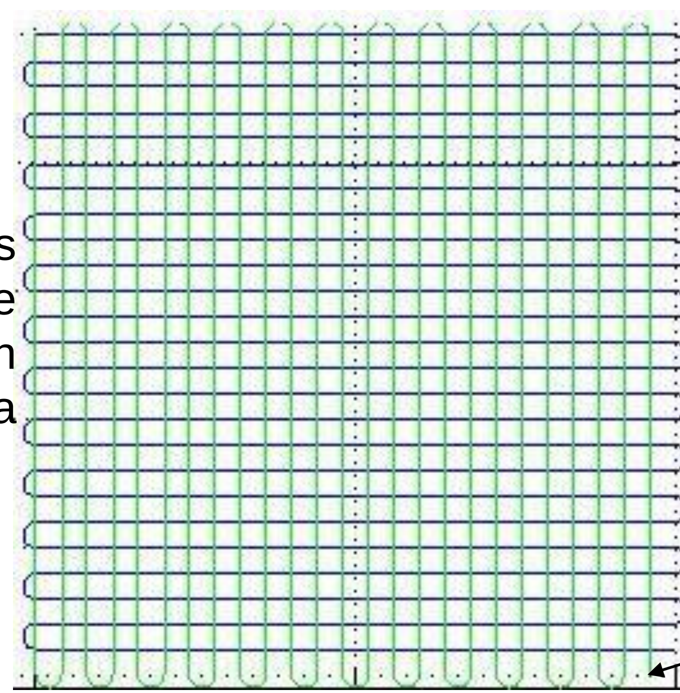
2 orthogonal lawnmower patterns is an established method for multiple aspect surveys. The minehunting mission is not completed faster, but the confidence that all mines have been detected will be higher.



Search area divided by number of available AUVs

AUV1 Start

Minehunting AUVs start from opposite corners of the search area



AUV2 Start

From simulation by author

AUV Survey Problems

3 problems impact AUV minehunting:

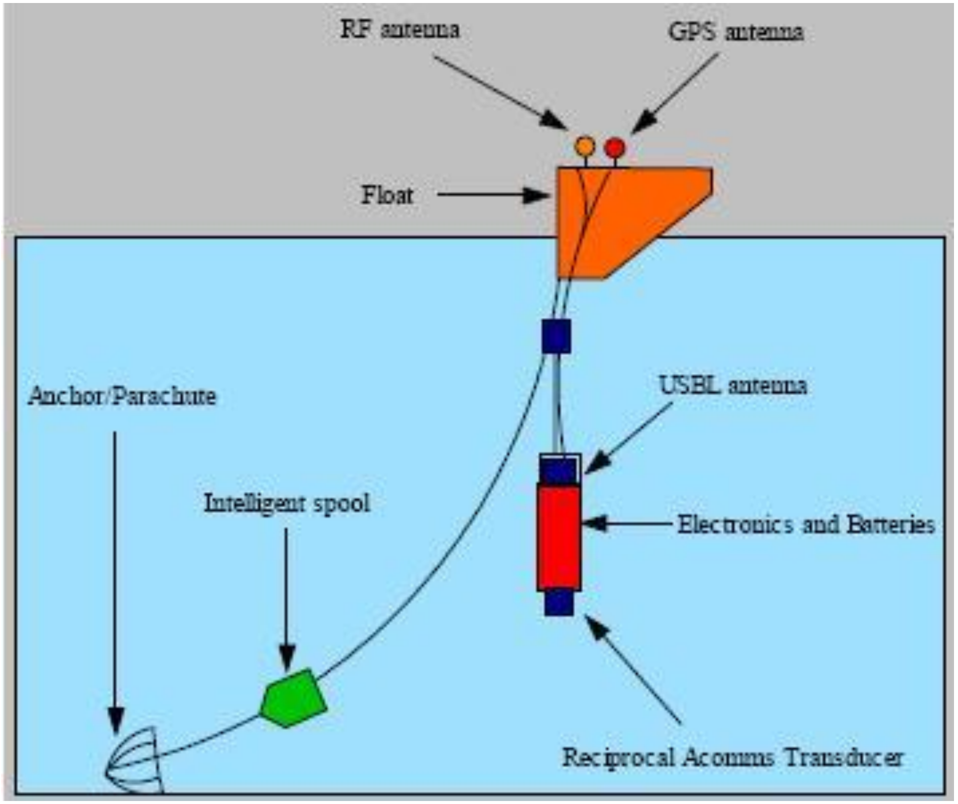
1. Area coverage rate – AUVs cannot hunt for mines anywhere near as fast as surface vessels
2. Communication
   – RF comm not viable option u/water
   – Acoustic comm has limited bandwidth and is not always reliable
3. Navigation
   – Not able to use RF or satellite-based systems (GPS, etc) u/water
   – Dead reckoning error grows with time unless reset periodically; good INS very expensive.
   – Dead reckoning must be aided by acoustic network, Simultaneous Localization and Mapping (SLAM), and/or GPS

Collaborative AUV Solution

- Coverage rate issue can be overcome by using multiple AUVs
- A solution to navigation and communication problems is to use an additional “asset” to aid navigation and communication :
  - – Field of specialized buoys
  - – Single additional, specially-tasked vehicle

Comm/Nav Options - buoys

1. Stationary Gateway Buoy: could be used for both communications and navigation; could deploy 2 or more – might not be recovered at end of mission.



Driscol, et al., “Development and Testing of an A-sized Rapidly Deployable Navigation and Communication GATEWAY Buoy,” ~2003.

Comm/Nav Options - Vehicles

2. Mobile Platform – 1 vehicle acts as a link between AUVs, command station, and as a navigation aid – a “beacon” or CNA (Communication and Navigation Aid) vehicle

- Deploy only 1 vehicle rather than several buoys
- Vehicle can track its way through optimal path
- Vehicle recovered at end of mission

Comm/Nav Vehicles, Cont'd

Two Mobile Platform Options

a. AUV:
- Variable depth—overcome comm blackouts from thermal or topographic boundaries
- Vulnerable on the surface
- Could act as investigating/classifying vehicle if nav accuracy of survey AUVs permits

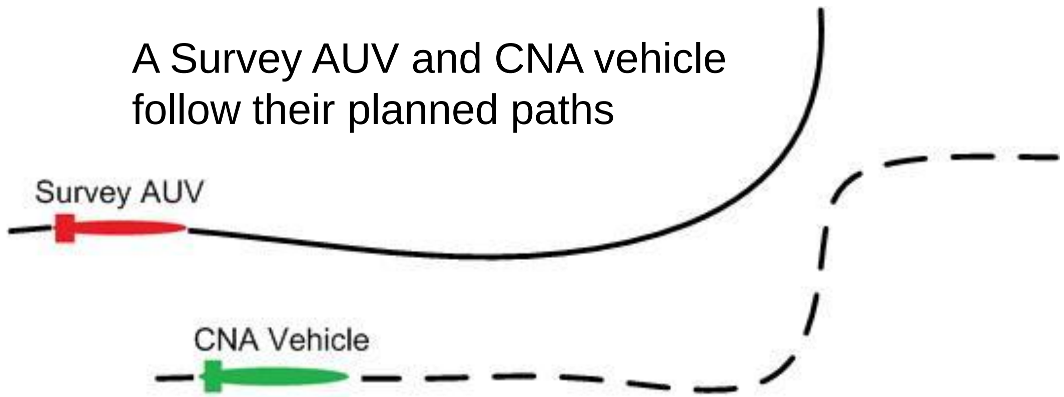
b. ASC (Autonomous Surface Craft):
- Constant acoustic and RF/Satellite connection
- Potentially moves faster than AUV (depends on platform)
- Less vulnerable on the surface

Previous Research

- CNA concept has been widely discussed including: Fallon, 2009, 2010b; Bahr, 2009; Chitre, 2010; Rui, 2010
- (Alternatives by Fallon, 2010a and Yoon 2010)
- Little previous work on path planning for CNA vehicle (Bahr, 2009; Chitre, 2010; Fallon, 2010b)
- Cooperative localization done by range only
- **Relative depth, thermal/topographic changes, and variable speed not considered in previous CNA path planning work**
- Survey AUV search patterns were very simple
- Cost/navigational accuracy trade-offs among buoys, ASCs, and AUVs not reported

Range-only Localization – 1 CNA vehicle

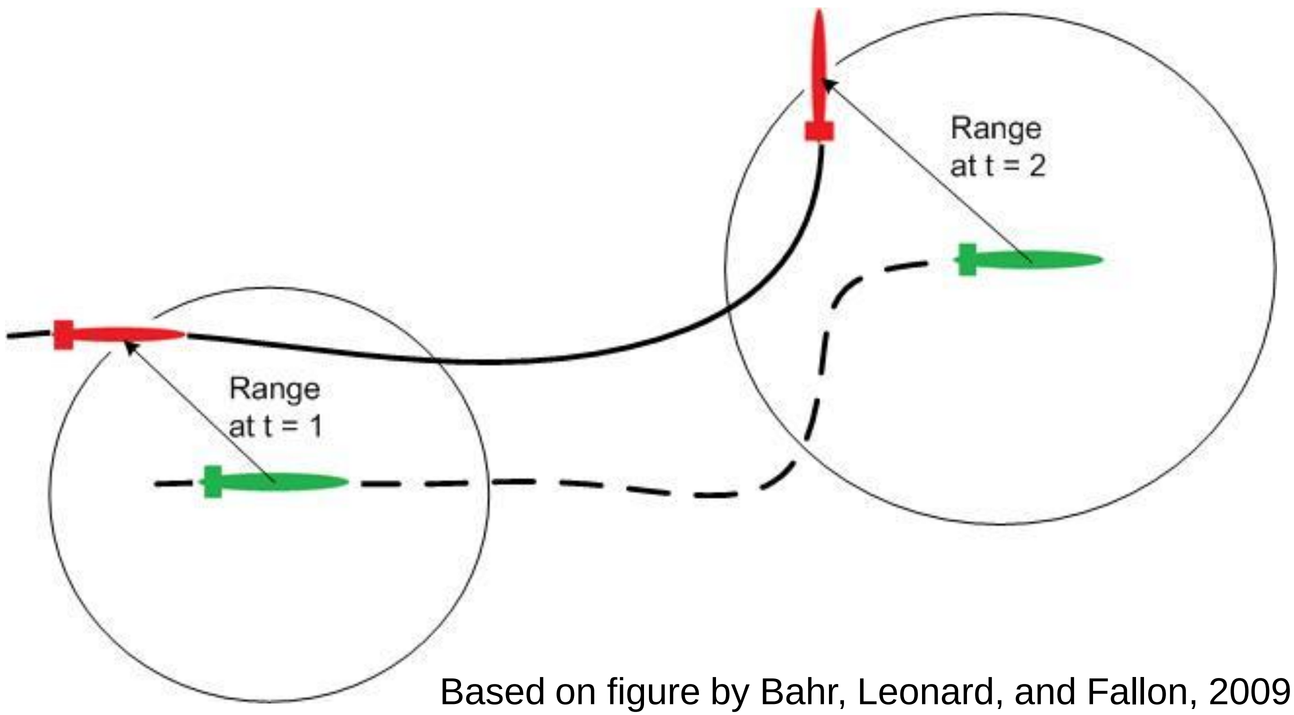
A Survey AUV and CNA vehicle
follow their planned paths



Based on figure by Bahr, Leonard, and Fallon, 2009.

Range-only Localization – 1 CNA vehicle

• AUV measures range from CNA at t=1 and t=2 with acoustic modem.



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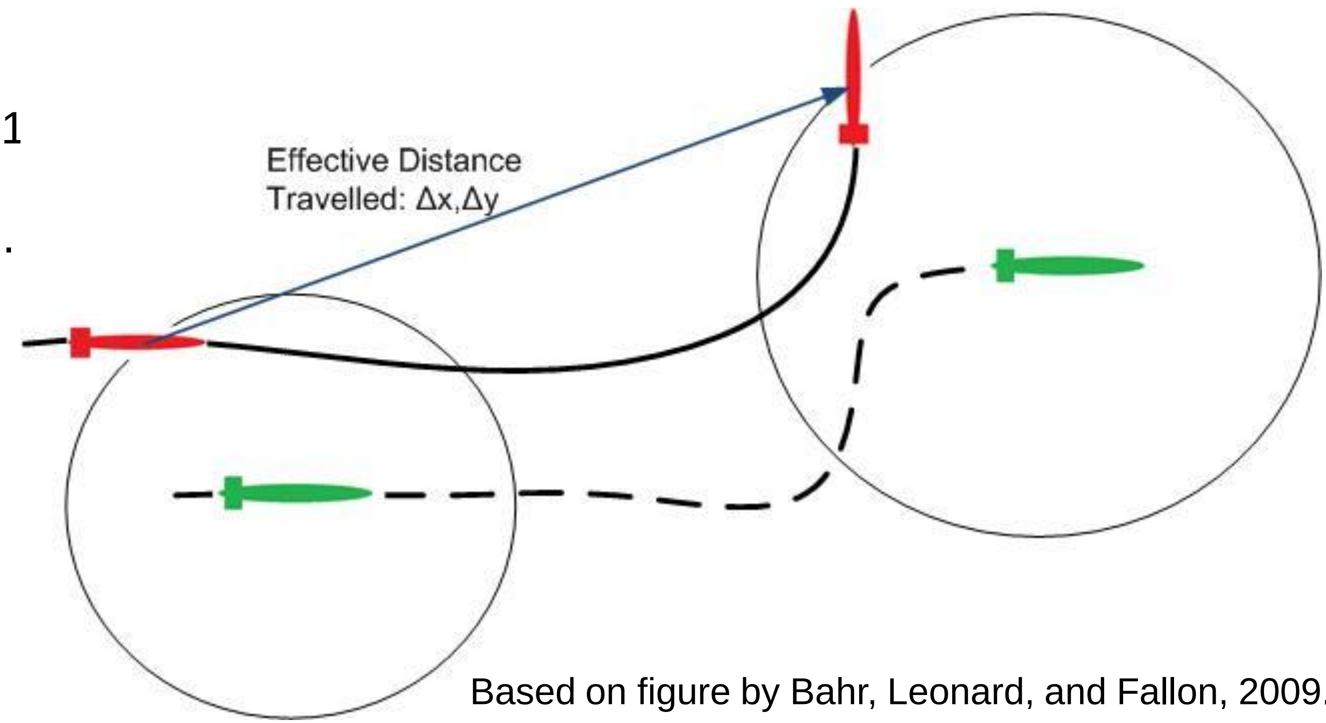
- AUV measures range from CNA at t=1 and t=2 with acoustic modem.
- Effective distance travelled by AUV from t=1 to t=2 measured by on-board navigation system.



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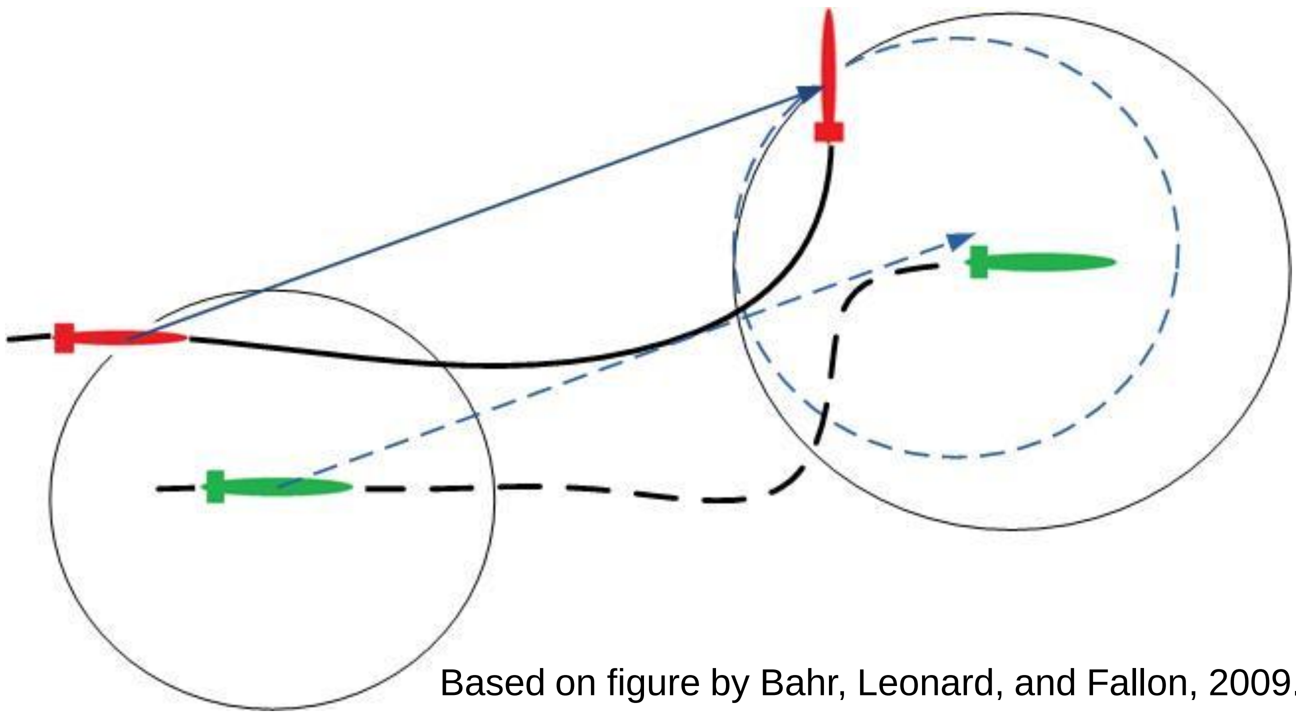

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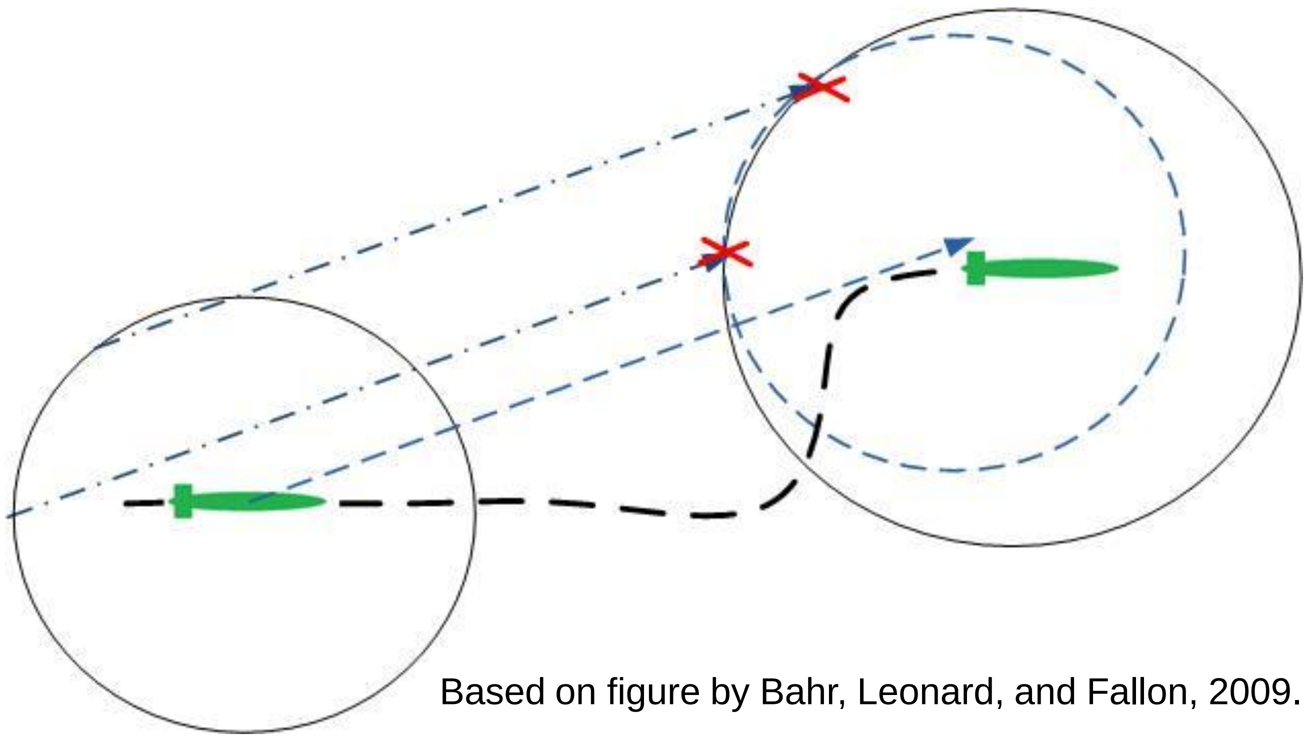

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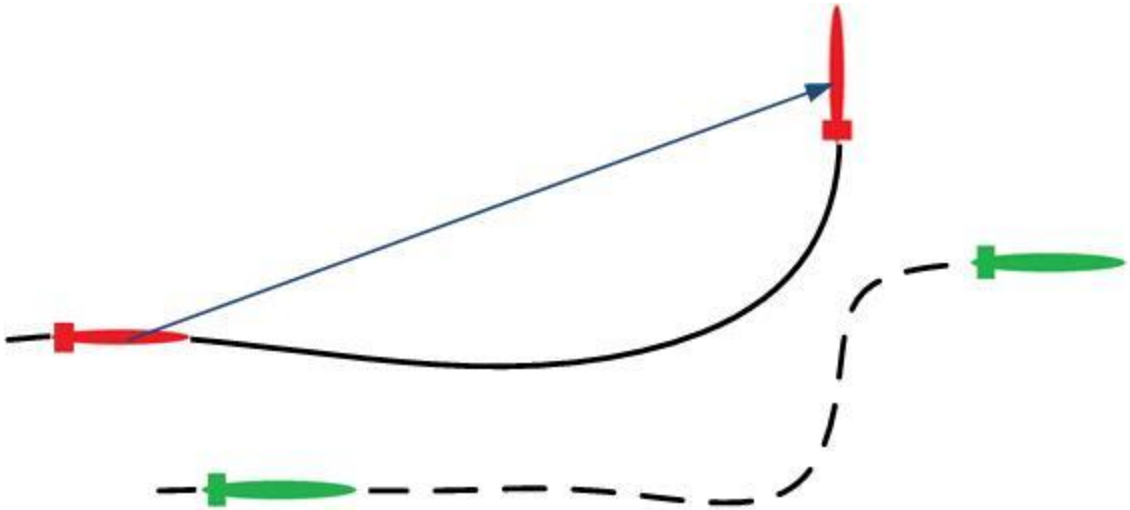
- Range circle from t=1 is projected the effective distance travelled.
- AUV position at t=2 is reduced to 2 possibilities by the intersection of the t=2 range circle with the projection of the t=1 range circle.
- Since survey AUV position at t=1 is known, its position at t=2 can be determined.



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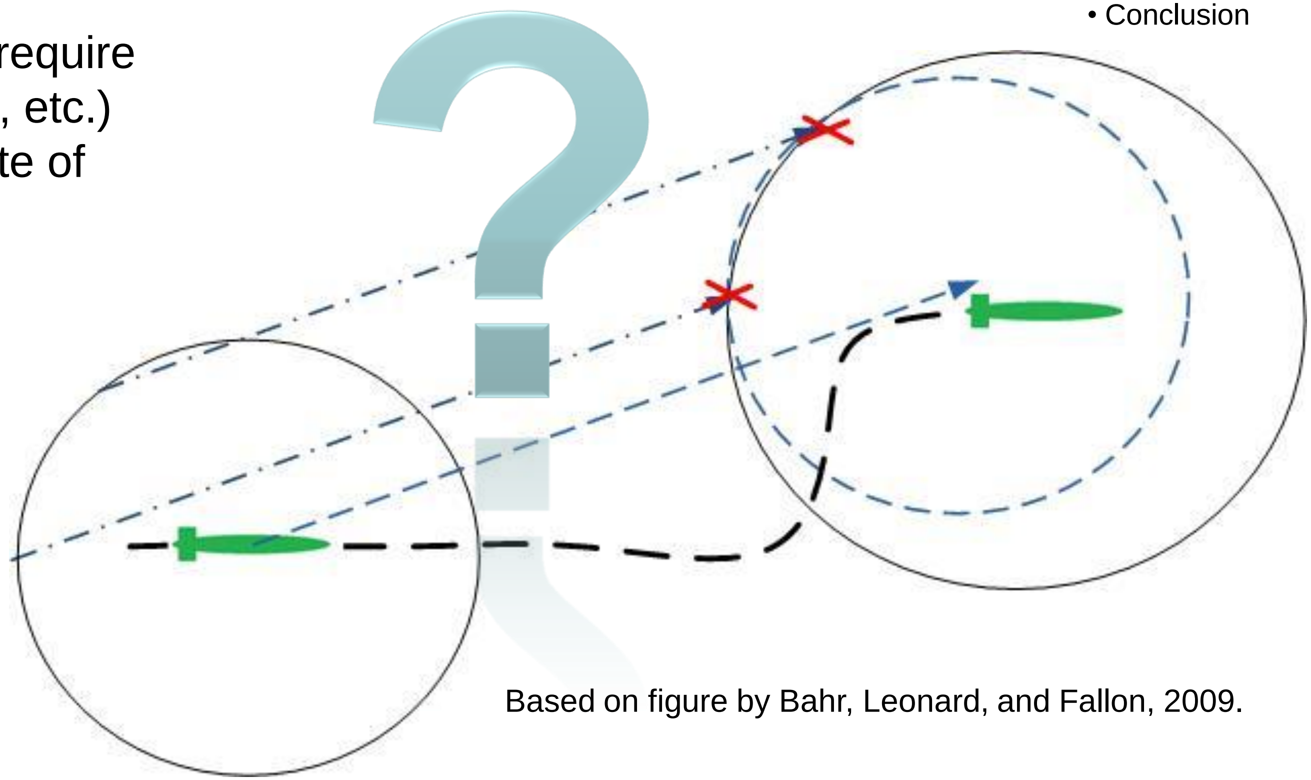
Range-only Localization – 1 CNA vehicle

Uncertainties in ranges, positions, and odometry require filtering (Kalman, particle, etc.) to determine best estimate of actual AUV position.



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2D CNA Path Planning

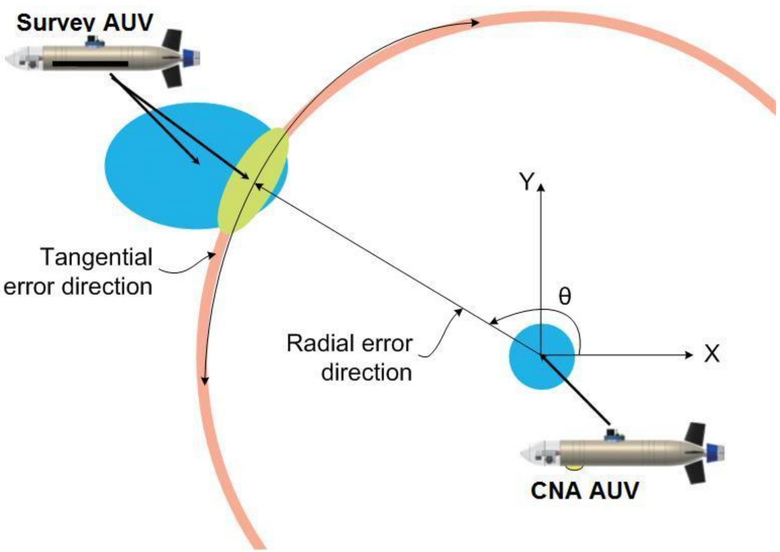
Outline

CNA path planning to minimize survey AUV position error

(Equations from Chitre, 2010)
CNA vehicle makes decision to change heading by δ:

$$\phi_{t+1}^{B} = \phi_{t}^{B} + \delta_{t}^{B}$$

$$x_{t+1}^{B} = x_{t}^{B} + t \cdot s^{B} \begin{pmatrix} \cos \phi_{t+1}^{B} \\ \sin \phi_{t+1}^{B} \end{pmatrix}$$



Adapted from Rui and Chitre, 2010

If the CNA's next position is along the tangential error direction, the error ellipse will reduce significantly. Similar effect to Bahr, 2009, with 2 CNA vehicles.

Error calculation:

$$\theta_{t+1}^{j} = \angle\left(x_{t+1}^{j} - x_{t+1}^{B}\right)$$

$$\gamma_{t}^{j} = \theta_{t+1}^{j} - \theta_{t}^{j}$$

$$\varepsilon_{t+1}^{j} = \sigma$$

$$\varepsilon_{t+1}^{-j} = \sqrt{\frac{\left(\varepsilon_{t}^{j}\varepsilon_{t}^{-j}\right)^{2}}{\left(\varepsilon_{t}^{j}\cos\gamma_{t}^{j}\right)^{2} + \left(\varepsilon_{t}^{-j}\sin\gamma_{t}^{j}\right)^{2}} + \alpha\tau}$$

- Survey AUV Errors are calculated for each CNA heading.
- CNA picks a heading to minimize error equation
- CNA can 'look ahead' to choose heading now to reduce error in later time steps – avoid painting yourself into a corner.
- Resulting path is similar to the planned encirclement described by Fallon, 2010b.

3D CNA Path Planning

Previously reported path planning for a CNA vehicle does not consider changes in depth by the survey AUV.

Minehunting AUVs may have to make large changes in depth to maintain a specified altitude above the ocean floor.

A CNA path that considers the survey AUV depth could significantly improve the effectiveness of the navigation aid even if the CNA vehicle cannot change depth (i.e. ASC)

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3D CNA Path Planning

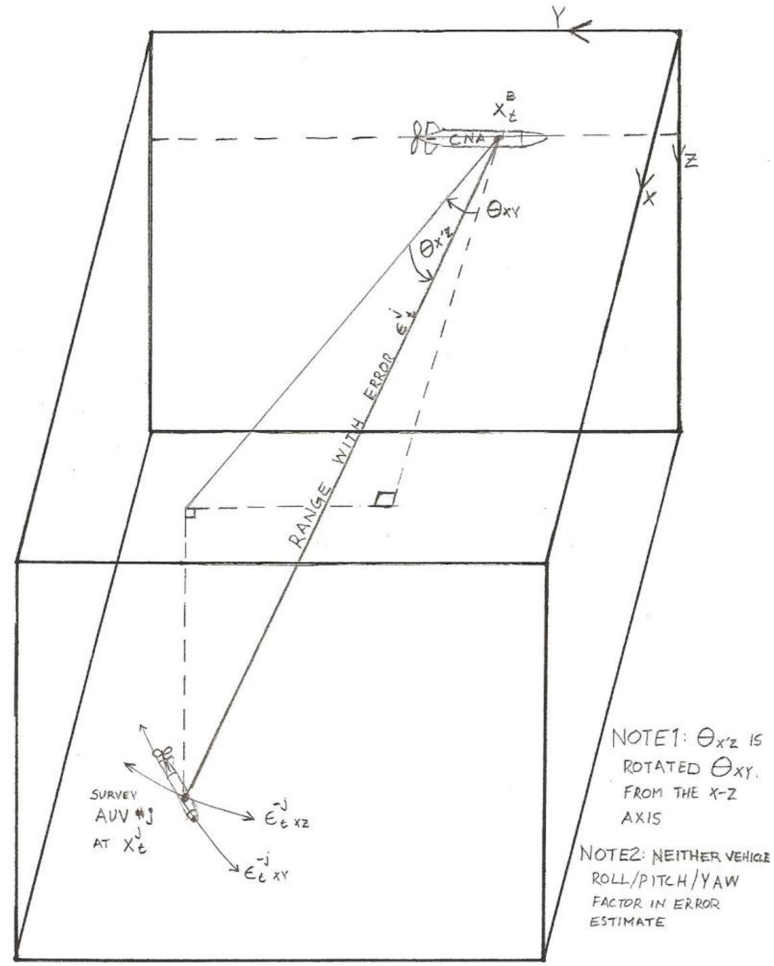
Outline
- Survey Patterns
- AUV Limits
- CNA Concept
- Path Planning
- Progress
- Future Work
- Conclusion

Proposition: Expand Chitre's equations to consider depth

1st Approach:

- survey AUV's position confined to an ellipsoid instead of a 2D ellipse.
- The CNA vehicle still tries to plan a path that minimizes the size of the ellipsoid

HOWEVER: AUVs assumed to have accurate depth sensors making uncertainty in depth negligible.



3D CNA Path Planning

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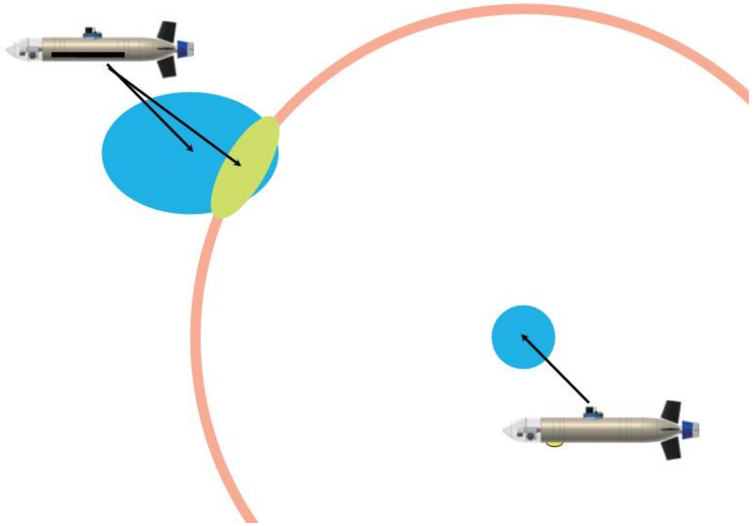


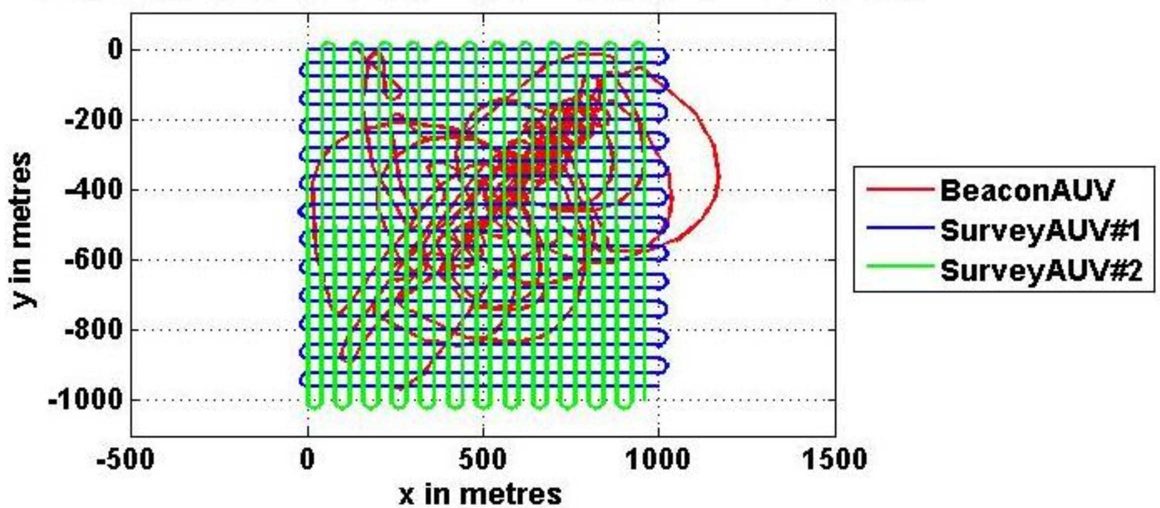
From Rui and Chitre, 2010

2nd Approach
• Continue path planning in previous manner as uncertainty remains in x-y plane.
• CNA vehicle continues to plan a path to minimize survey AUV error

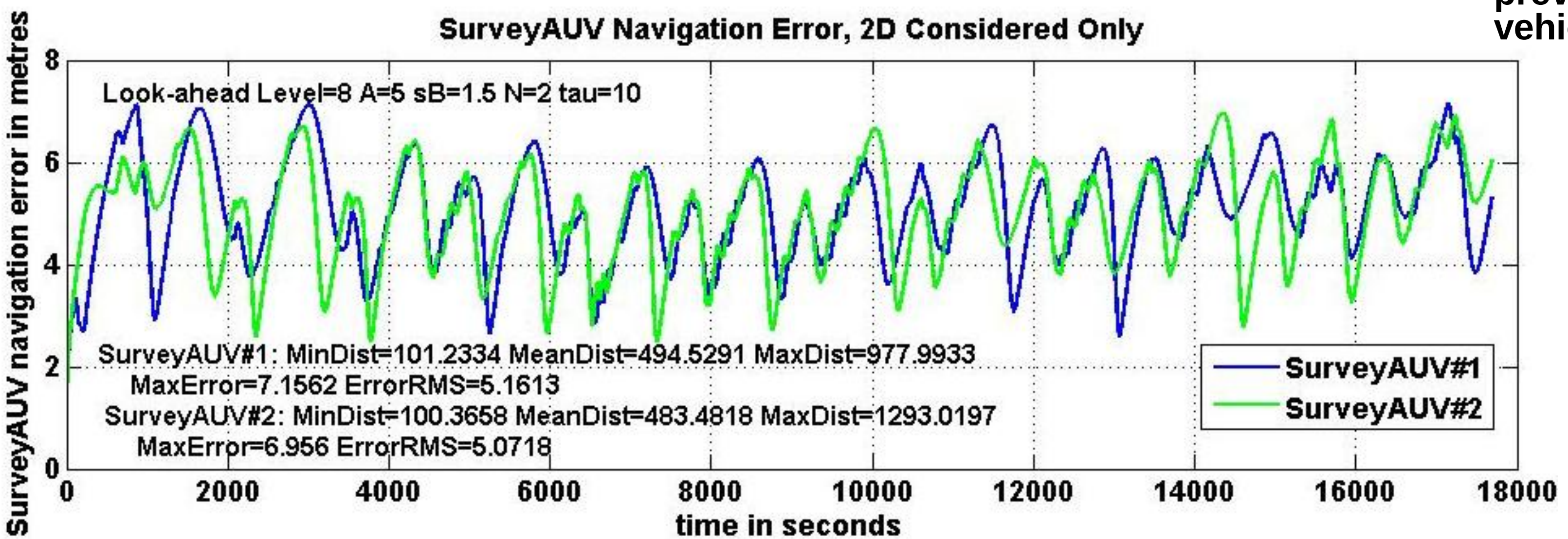
Progress To Date

1. Simulations of CNA vehicle path planning in 2D (building on Chitre, 2010)
2. Incorporated energy consumption estimate during **CNA** AUV mission—provides indication of feasibility of the mission—not reported in previous CNA AUV work
3. Expanded CNA vehicle path planning into 3D allowing for both AUV and ASC CNA vehicles. This represents a **new development** in CNA work.

2D Path Planning



2D Simulation of CNA vehicle tracking 2 survey AUVs on orthogonal paths. **This pattern has not been used in previous CNA vehicle work.**



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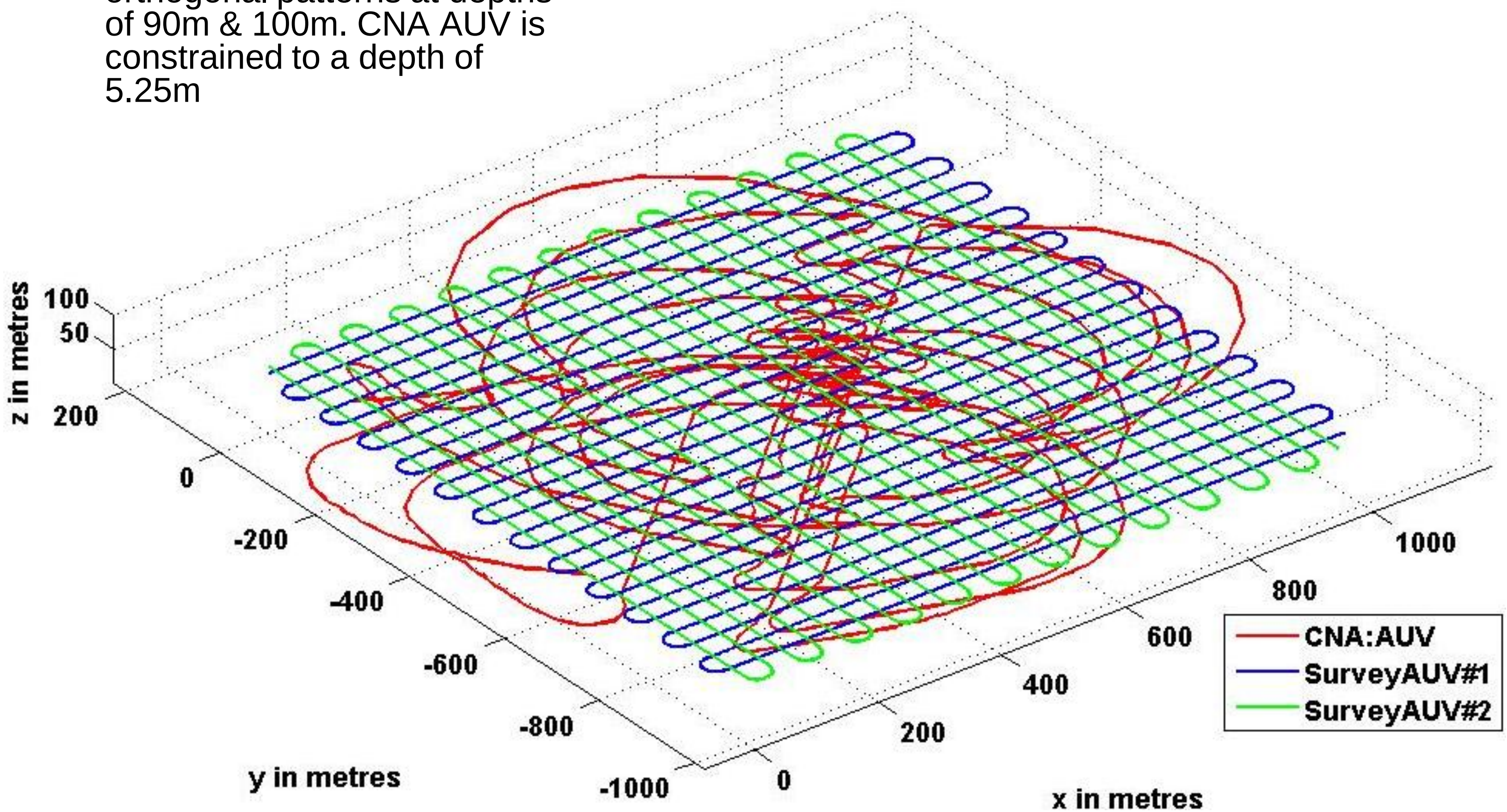
3D Path Planning

3D Simulation of a CNA AUV tracking 2 survey AUVs on orthogonal patterns at depths of 90m & 100m. CNA AUV is constrained to a depth of 5.25m



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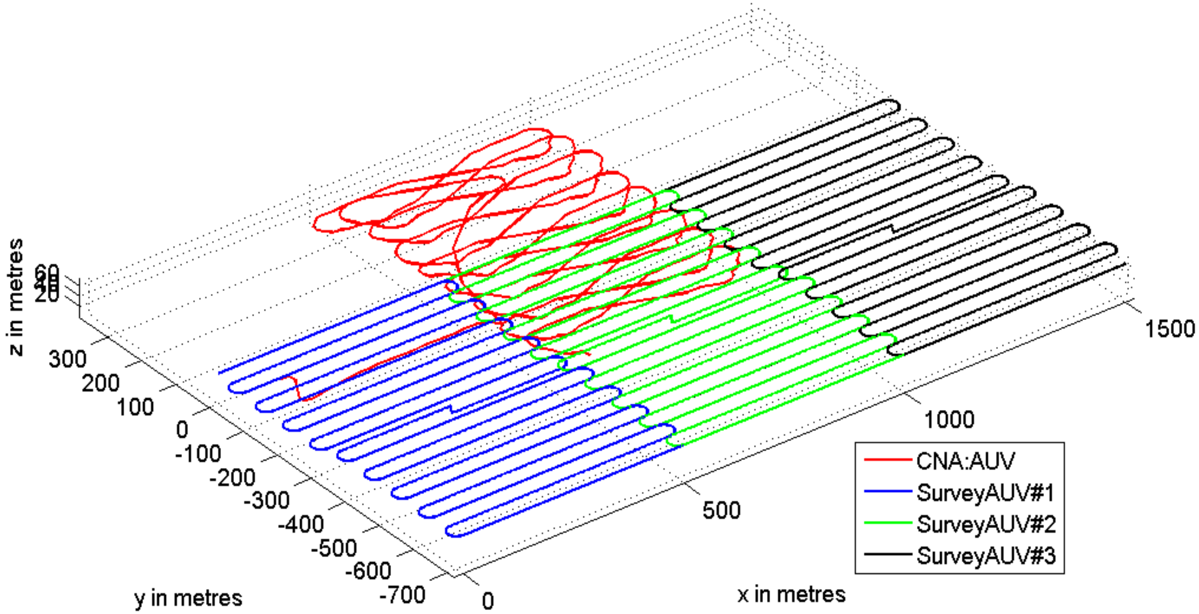
3D Path Planning



3D Simulation of CNA AUV tracking 3 survey AUVs.

Survey AUVs begin at 60m depth and increase depth to 75m half-way through mission.

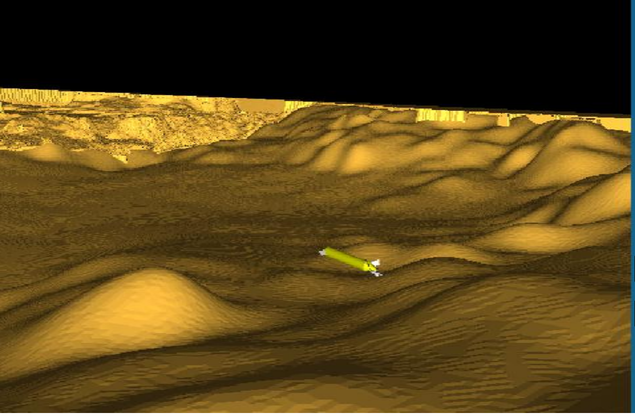
Table 1: AUV or ASC CNA with 1 Survey AUV

		Distance (m)			Error (m)	
CNA	sB (m/s)	Min	Mean	Max	Max	RMS
AUV	1.5	100.344	236.601	456.225	4.750	3.578
AUV	2.0	101.206	262.018	566.598	5.040	3.519
ASC	1.5	100.392	240.872	461.629	4.809	3.599
ASC	2.0	100.220	235.622	556.280	4.891	3.386
ASC	3.0	100.018	108.063	160.721	2.942	2.454

Table 2: AUV or ASC CNA with 3 Survey AUVs

		Max Error (m)			RMS Error (m)		
CNA	sB (m/s)	AUV1	AUV2	AUV3	AUV1	AUV2	AUV3
AUV	1.5	6.802	6.135	6.809	5.870	4.772	5.941
AUV	2.0	6.465	5.576	6.446	5.341	4.267	5.397
ASC	1.5	6.803	6.102	6.795	5.874	4.765	5.936
ASC	2.0	6.465	5.602	6.457	5.346	4.264	5.401
ASC	3.0	5.915	4.860	5.854	4.613	3.860	4.665

No benefit seen with AUV use, but increasing speed improves performance.



Picture from
Popa, 2010

Future Work

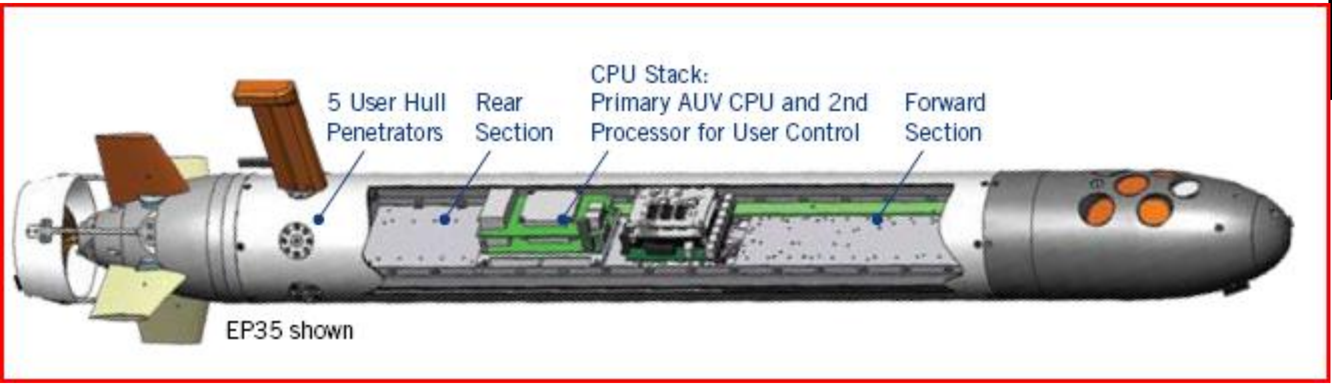
1. Apply 3D CNA path planning in the simulation component of DRDC Multi-Agent System for more realistic simulation. This simulation environment will make it easier to eliminate some of the assumptions implicit in my current work, such as:
   a. CNA’s knowledge of it’s position doesn’t degrade
   b. All messages between vehicles are received

Future Work, Cont'd

2. Test algorithms with IVER2s

• DRDC has acquired 1 IVER2 AUV and is purchasing a second IVER2. IVER2's small size and flexible sensor suite makes it useful for development work. I plan to use the IVER2s for testing 3D CNA path planning.

OceanServer website



OceanServer website

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Future Work

Questions from the Big Picture:

- Is an AUV or ASC a better CNA vehicle?
- Is either better than using buoys?
- Based on what measures of performance?
  - Survey AUV navigation accuracy
  - Energy Consumption
  - Specific survey patterns
- Do these conclusions apply beyond the MCM mission?

Conclusion

1. A CNA vehicle is a collaborative solution to the communication and navigation issues in AUV operations.
2. Results for 3-dimensional path planning simulations of a CNA vehicle do not currently suggest that AUV CNA to be measurably better or worse than a ASC CNA.
3. More research needs to be done.

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Thank you

Questions?