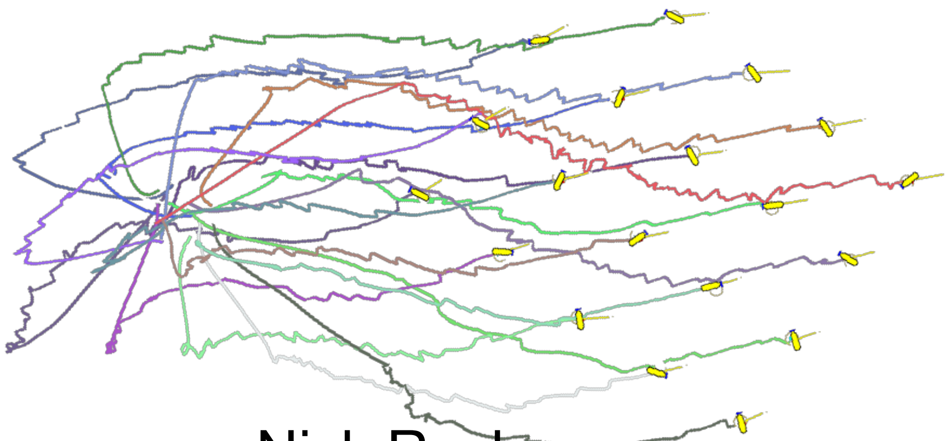
Distributed Autonomy and Formation Control of a Drifting Swarm of Autonomous Underwater Vehicles



Nick Rypkema

MIT/WHOI Joint Program (rypkema at mit dot edu)

Henrik Schmidt

MIT Laboratory for Autonomous Marine Sensing Systems

Massachusetts Institute of Technology

MIT WHOI

JOINT PROGRAM IN OCEANOGRAPHY/APPLIED OCEAN SCIENCE & ENGINEERING

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Motivation and Goals

- Use a 'swarm' of AUVs to sample oceanographic processes, e.g:
  - Monitor dynamic phenomena such as phytoplankton blooms over spatial grid
  - Use swarm as a 'virtual' acoustic receiver array for seismic surveying and detection of acoustic radiation
- Improve mission endurance by utilizing ocean currents to propel the swarm
- Investigate distributed formation control behaviours and implement with associated infrastructure in MOOS-IvP
- Implement MOOSApp for efficient batch request of simulated ocean data from MSEAS NetCDF files for realistic ocean currents

Swarm Robotics

- Application of Swarm Intelligence concepts to multi-robot systems – how collective behavior of a multi-robot system emerges from local agent-agent and agent-environment interaction [1].
- Often inspired by biological systems, e.g. ants, bees, bird flocks, fish schools, bacteria [2].
- Advantages: greater sensing capability, robustness against mission failure, parallelization of mission tasks, adaptable & scalable, cost effective.
- Disadvantages: command & control is difficult, how to deploy and retrieve, emergent behavior difficult to predict.
- Design considerations - architecture and application:

Architecture:
- Control – centralized vs decentralized vs distributed
- Agents – homogeneous vs heterogeneous
- Communication – completely connected vs locally connected (range based?)

Application (how to address mission):
- Behaviors – aggregation, dispersion, task allocation, coordinated collective motion, object transportation, collective exploration and mapping, pattern formation, etc.

1) G. Beni (2005) 2) A. Jevtic (2012), C.W. Reynolds (1987), A. Shklarsh (2011)

Swarm Robotics Underwater

- Underwater Environment Considerations:

Acoustic Communication:

- Problem: highly limited by low bandwidth and intermittency (multipath, ambient noise, attenuation), plus message collision due to large number of agents
- Solution: control strategies that minimize communication are highly advantageous

Localization:

- Problem: no GPS, acoustic positioning infrastructure such as USBL/SBL/LBL unwieldy, accurate INS expensive
- Solution: agents navigate relative to neighbours (local frame of reference) + postprocessing

- AUV Swarm Design Considerations:

Architecture:

- Control – distributed (acoustic comms insufficient for central control)
- Agents – homogeneous (single-type low-cost AUVs, e.g. biological sensors or acoustic sensors)
- Communication – short-range locally connected (acoustic comms less reliable at longer ranges)

Application (how to address mission):

- Behaviors – pattern/lattice formation control

Distributed Formation Control

- Pattern/lattice formation control – behaviors that produce and control well defined geometric patterns of agents in the swarm (reviews of formation control strategies available from E. Bahceci (2003), Y.Q. Chen (2005)).

- Several type of approaches:

Physics-Based:	Potential Field:
• Inspired by the physics of atoms, crysals, or springs – uses virtual forces to coordinate the movement of agents • W. Spears (2004), C. Pinciroli (2008), V. Gazi (2002), K. Fujibayashi (2002), B. Shucker (2007), etc.	• Similar to physics-based, but uses global rather than local potential fields to move agents into desired formation shapes • R. Bachmayer (2002), L. Chaimowicz (2005), etc.
Virtual Structure: • Formation is treated as a single rigid body with agents as vertices – structure is defined and agents maintain a rigid geoemetrical relationship • M.A. Lewis (1997), C. Belta (2001), etc.	Leader-Follower: • Hierarchy of agents is defined in the formation, and followers attempt to maintain formation with their leader(s) – leader(s) follow a prescribed path, or their own leader(s) • J.P. Desai (2001)

- Very minimal work on underwater swarms, even less on underwater formation control – existing literature is mostly simulation (e.g. Z. Hu (2014) formation control with restricted information exchange, S. Kalantar (2007) physics-based shape control, J. Shao (2006) leader-follower formation control of biomimetic fish) or small scale experiments with custom-made miniature vehicles (e.g. A. Amory (2013) MONSUN II, T. Schmickl (2011) CoCoRo)

- No work using conventional torpedo-shaped AUVs – potential for significant impact in this field!

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Image: MONSUN vehicles

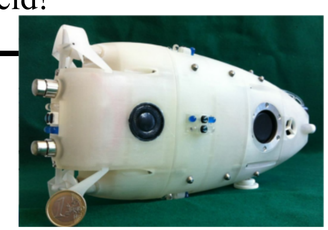
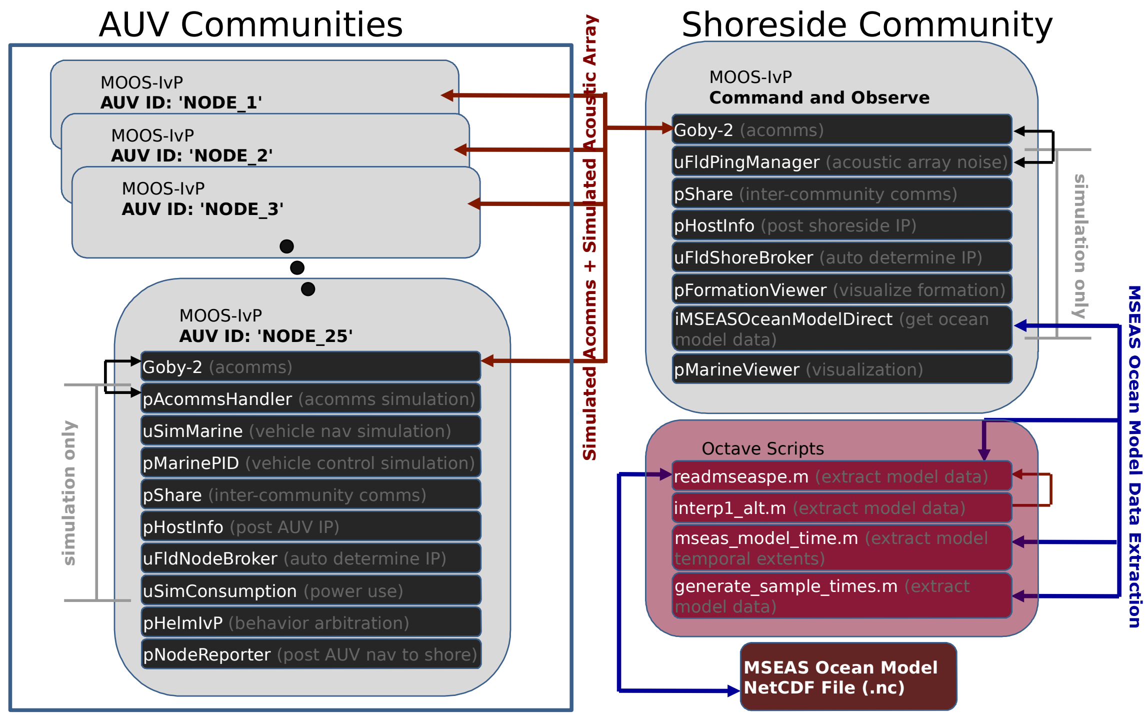


Image: CoCoRo vehicle

Approach – Simulation Infrastructure

- Simulation: MOOS Community for each AUV (vehicle dynamics/control, formation behaviors, energy consumption, etc.). MOOS 'shoreside' community (simulate acoustic comms, ocean currents, formation quality, etc.).
- Behaviours: 4 target-based behaviours for formation control, requiring bearing & range to neighbors, 2 require communication of unique vehicle IDs, 3 require user-specified plan. AUVs constantly reposition to a relative target calculated via locations of nearest neighbors.



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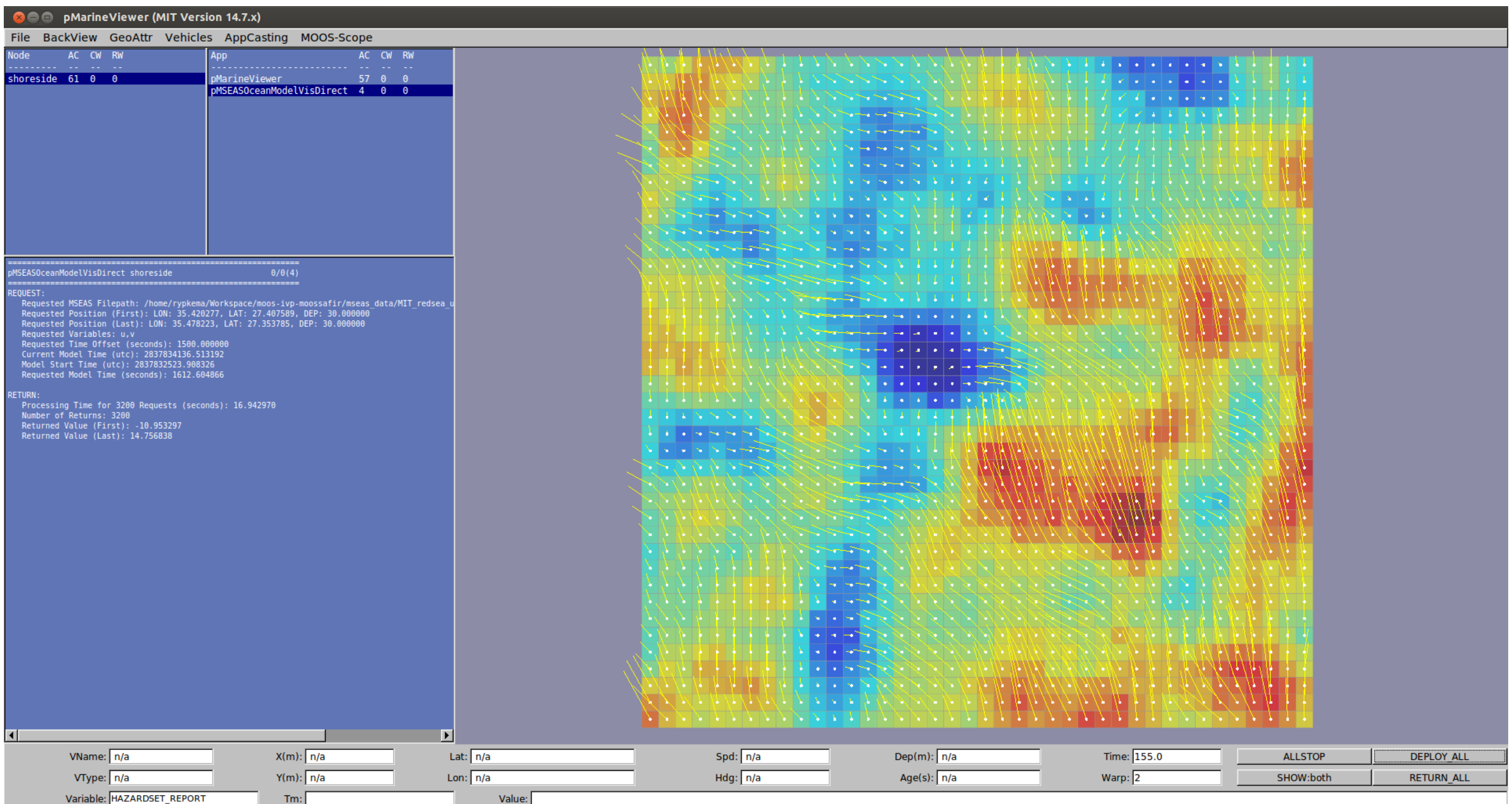
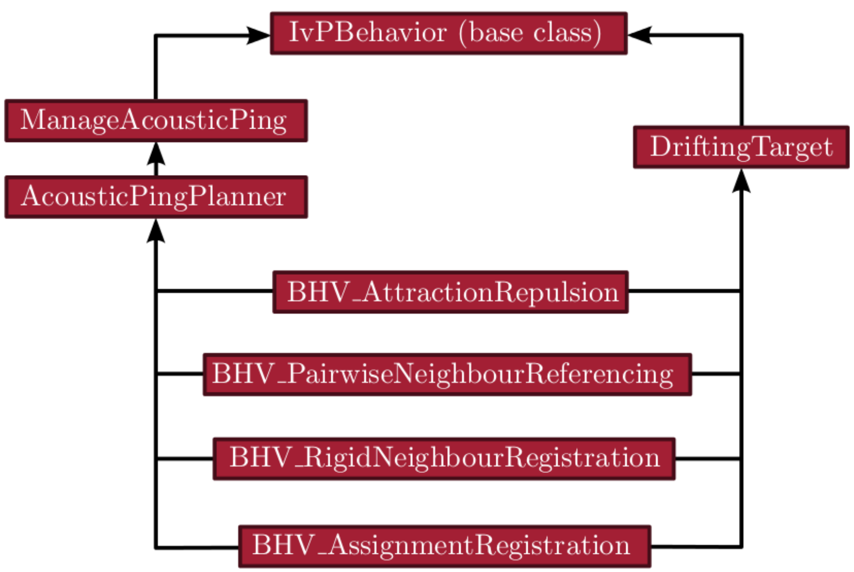
iMSEASOceanModelDirect

- MOOS-MSEAS interface for batch requests of ocean model data:
  - Uses an Octave translation of existing MSEAS Matlab script to perform multiple data requests with a single call



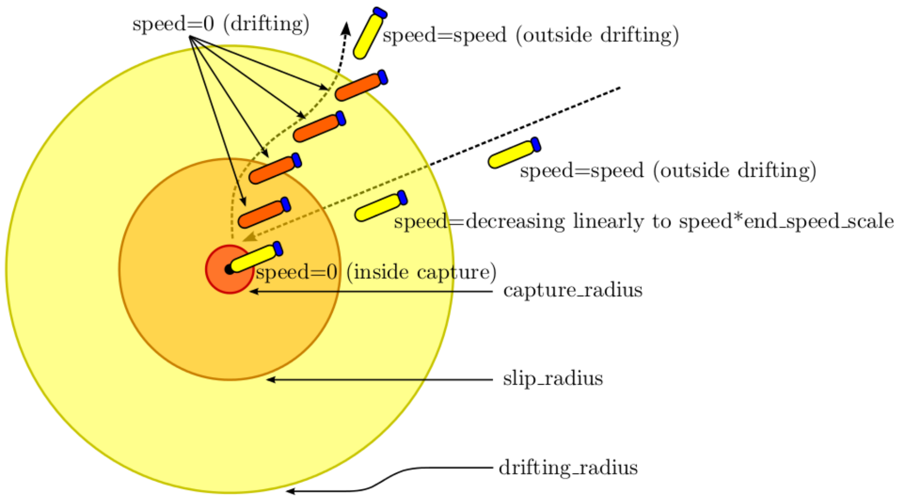
Behaviour Class Hierarchy

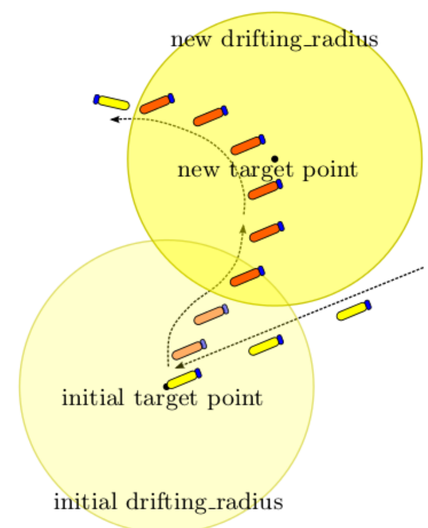
- Each formation control behaviour inherits functionality from:
  - DriftingTarget: directs AUV to optimal position in the formation
  - ManageAcousticPing: handles incoming acoustic pings (setting relative positions of neighbours)
  - AcousticPingPlanner: allows user to specify desired formation plan



DriftingTarget Behaviour

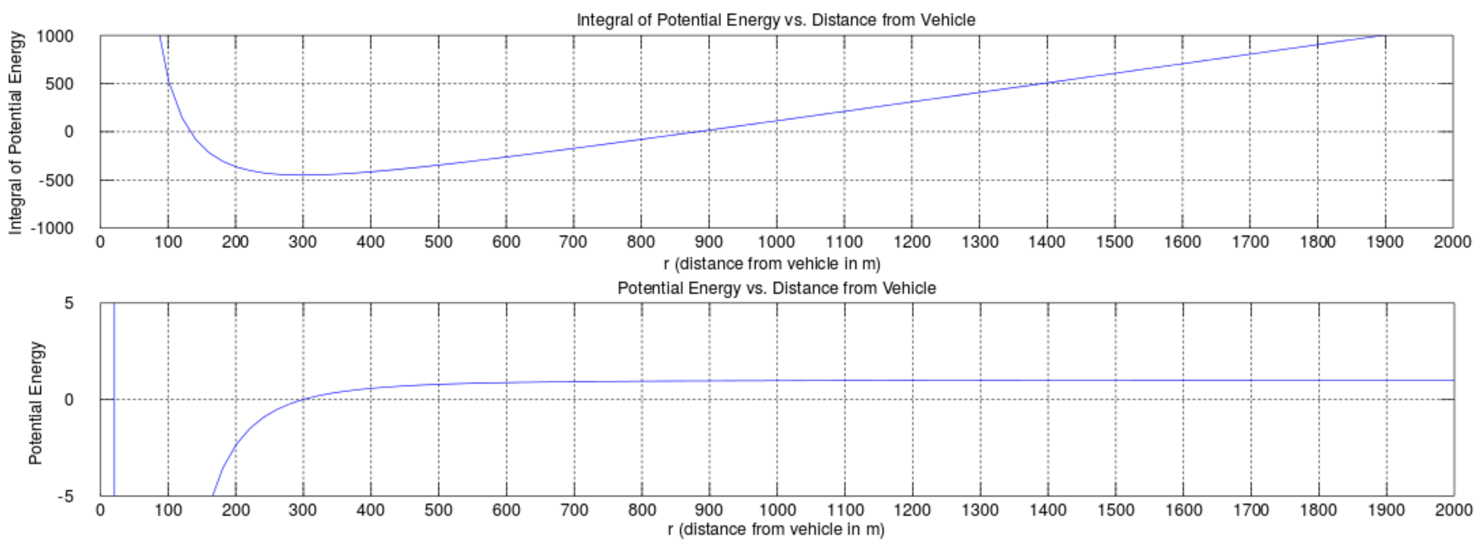
- Used to direct AUV to relative x/y position:
  - Hybrid of existing Waypoint and StationKeep behaviours
  - Trade-off between formation 'quality' and energy expenditure – smaller drifting radius forces AUVs to conform more tightly, but readjusts more often





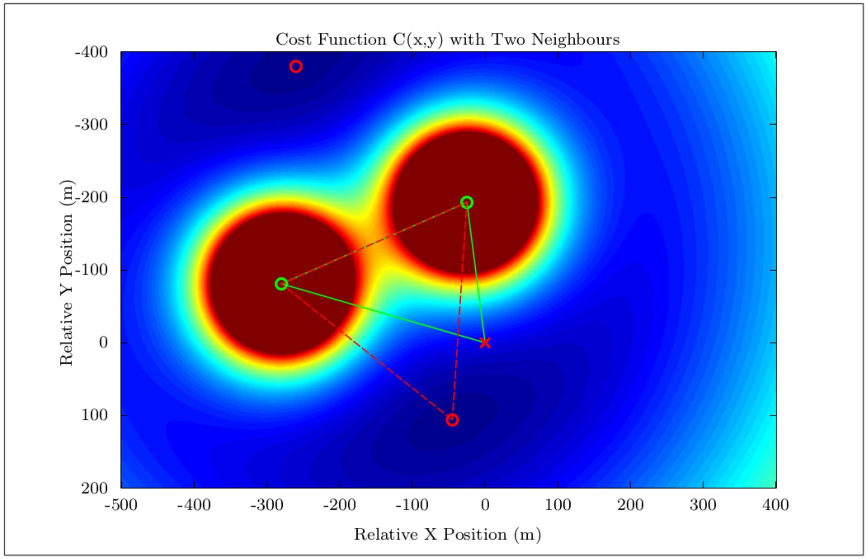
Formation Control 1 - BHV_AttractionRepulsion

- Inspired by existing physics-based approaches (atomic attraction/repulsion):
  - Only requires range/bearing to neighbours
  - Existing approaches use potential function (e.g. Lennard-Jones) to attract/repel neighbours – I use constant attraction/unbounded repulsion
  - I instead use integral of potential function, and perform direct non-linear optimization over surface using NLOpt library



Formation Control 1 - BHV_AttractionRepulsion

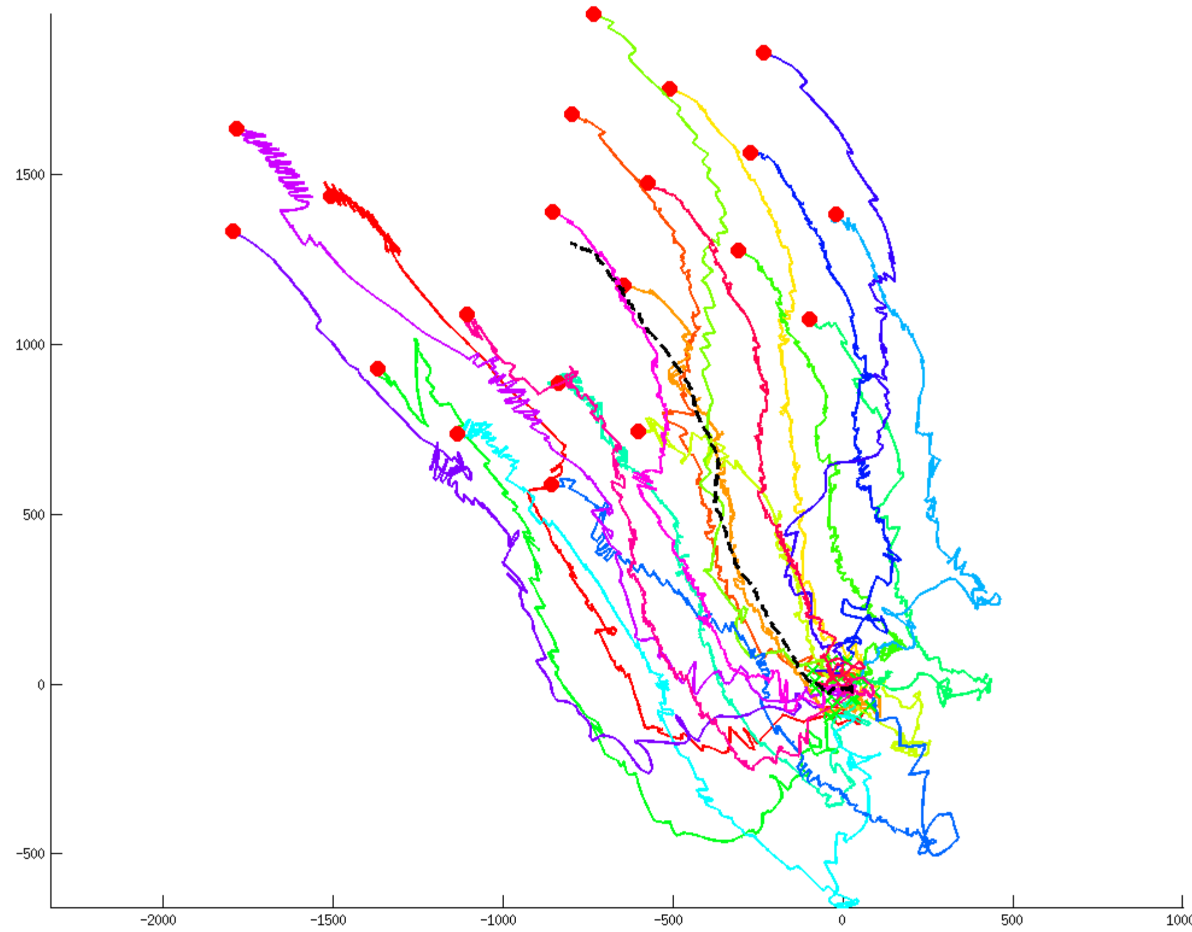
- Using all neighbours within a radius results in 'defects' caused by different summations of cost surfaces depending on number of neighbours
- Instead use only 2 neighbours – first selected as nearest, second selected such that sum of triangle edges is minimum



$$C(x,y) = \sum_{(x_i,y_i)\in N_s} \left(\frac{s^3}{2\cdot(\sqrt{(x-x_i)^2+(y-y_i)^2})^2}\right) + ((\sqrt{(x-x_i)^2+(y-y_i)^2}) - 3\cdot s)$$

$$+ 1e^{-5}\cdot(\sqrt{(x-\frac{\sum_{j=1}^{n}(x_j)}{n})^2+(y-\frac{\sum_{j=1}^{n}(y_j)}{n})^2})^2 \quad (3.7)$$

Formation Control 1 - BHV_AttractionRepulsion



Formation Control 2 - BHV_PairwiseNeighbourReferencing

- What can we do if we exchange globally unique IDs? Simple geometric approach:
  - Each pair of neighbours can be used as a reference axis – given a desired formation, each pair gives a relative target – use centroid of all targets

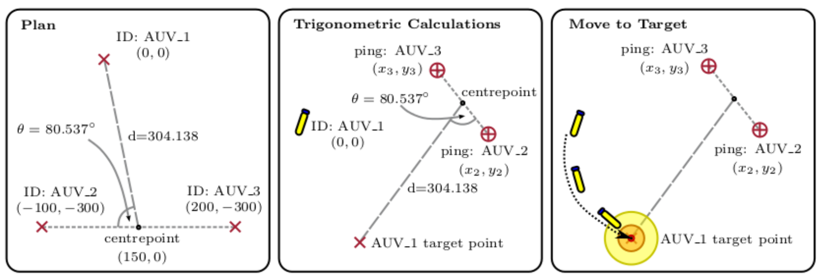


Figure 3.10: Illustration of the geometric principles behind BHV_PairwiseNeighbourReferencing running on AUV_1 for a single neighbour pair (AUV_2, AUV_3).

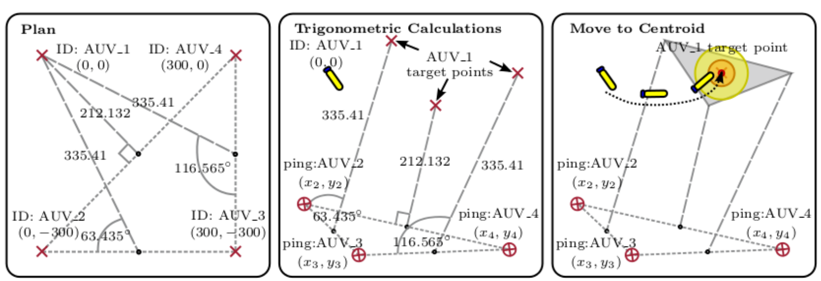
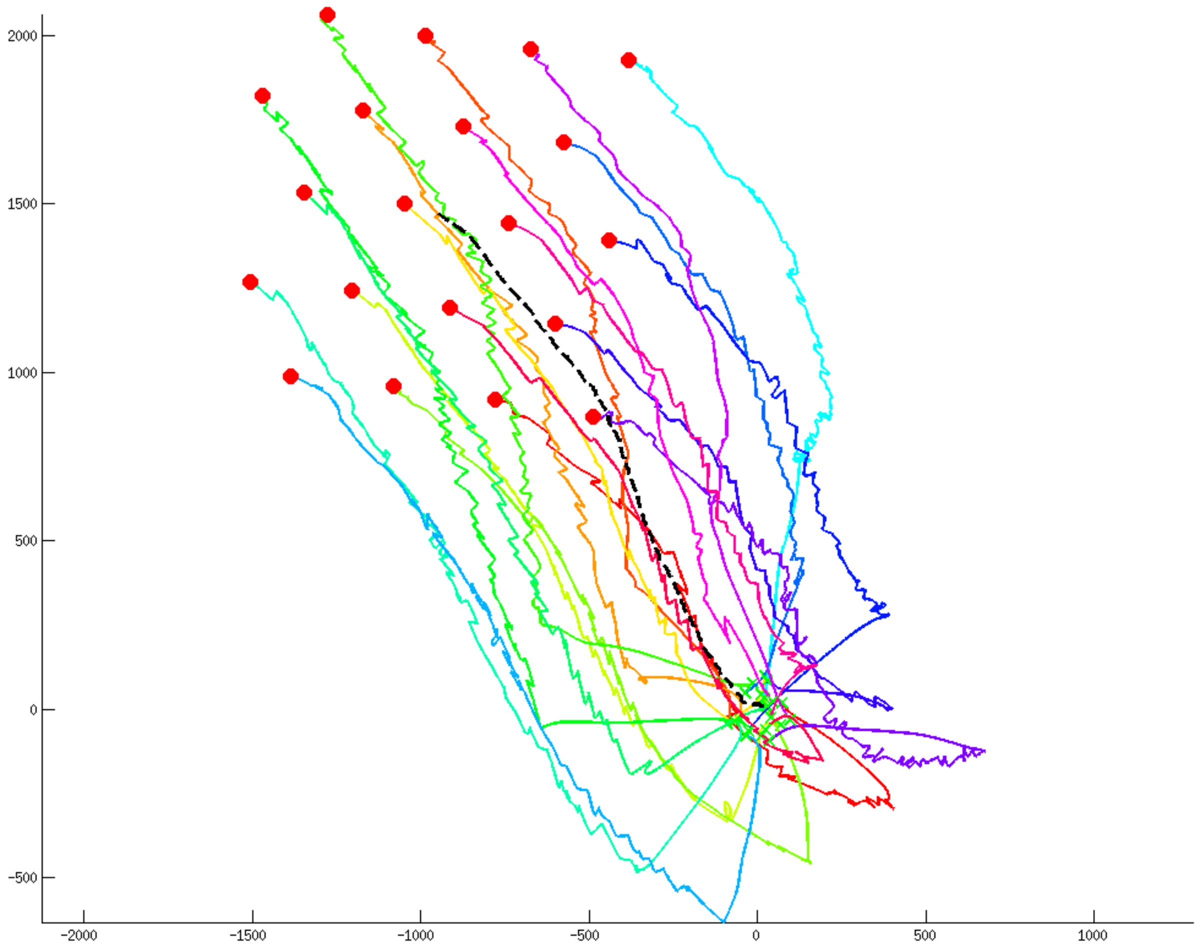


Figure 3.11: Illustration of the geometric principles behind BHV_PairwiseNeighbourReferencing running on AUV_1 for three neighbour pairs (AUV_2, AUV_3), (AUV_3, AUV_4) and (AUV_2, AUV_4).

Formation Control 2 - BHV_PairwiseNeighbourReferencing



Formation Control 3 - BHV_RigidNeighbourRegistration

- Can we improve? Inspired by ICP algorithm used to align point clouds – in our case, point correspondences are set explicitly, so just need to calculate optimal rigid transformation:
  - Orthogonal Procrustes/Rigid Point Set Registration problem, explicit solution using SVD available
  - Aligns two point sets (actual neighbour positions, and planned formation positions) optimally in the least-squares sense
  - Armadillo linear algebra library used in implementation

$$(R, \vec{t}) = \underset{R, \vec{t}}{\operatorname{argmin}} \sum_{i=1}^{n} w_i ||(R \begin{bmatrix} x_{pi} \\ y_{pi} \end{bmatrix} + \vec{t}) - \begin{bmatrix} x_i \\ y_i \end{bmatrix} ||^2$$

Formation Control 3 - BHV_RigidNeighbourRegistration

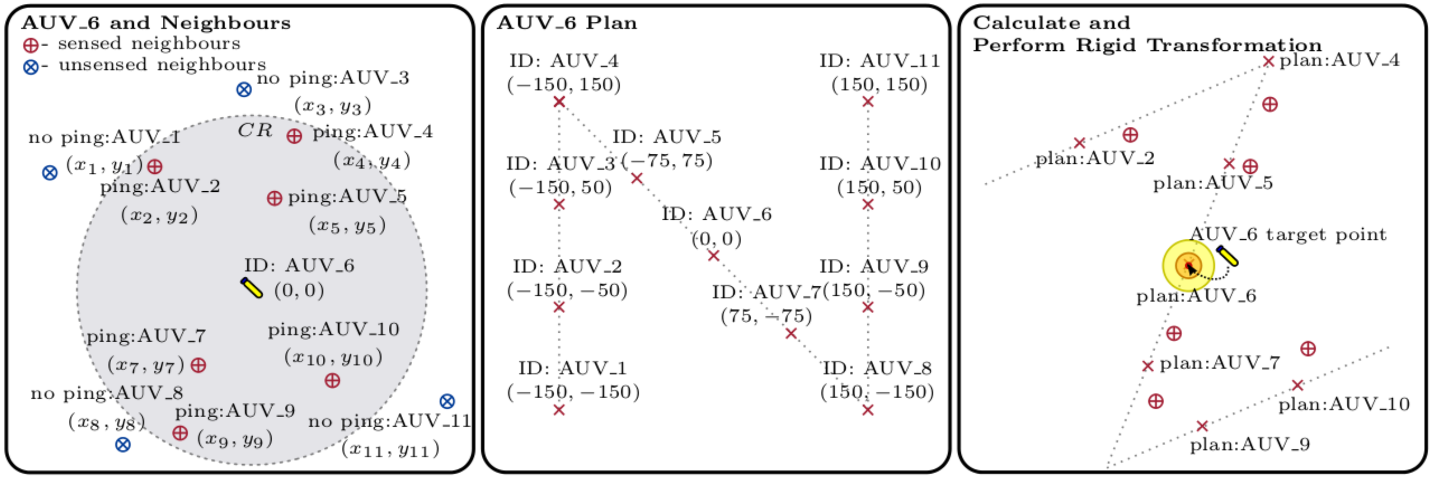
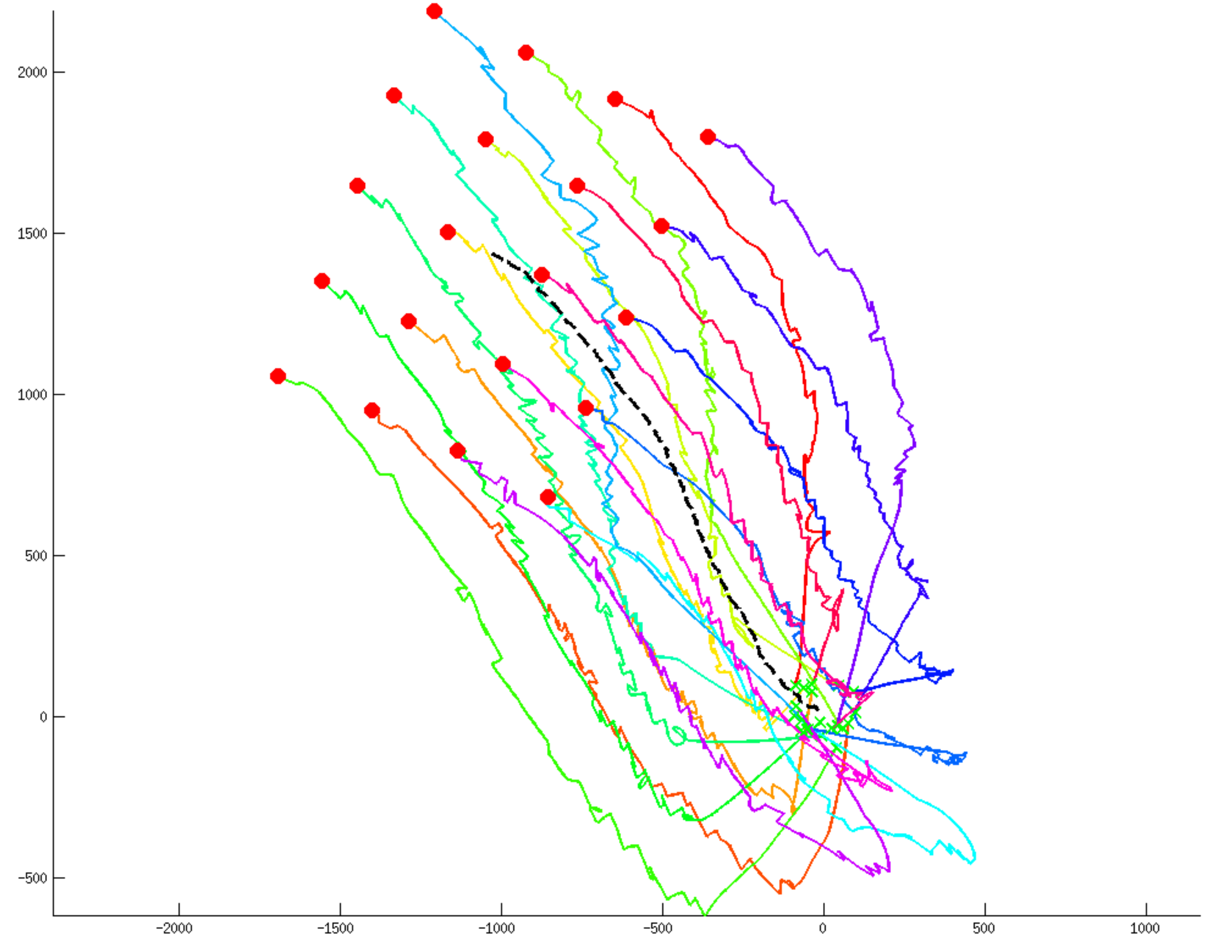


Figure 3.13: Illustration of the operational principles of BHV_RigidNeighbourRegistration; for the neighbours within the vehicles CR, the corresponding points from the plan are rotated and translated to best fit the actual neighbour positions (the CR is reduced for illustrative purposes).

Formation Control 3 - BHV_RigidNeighbourRegistration



Formation Control 4 - BHV_AssignmentRegistration

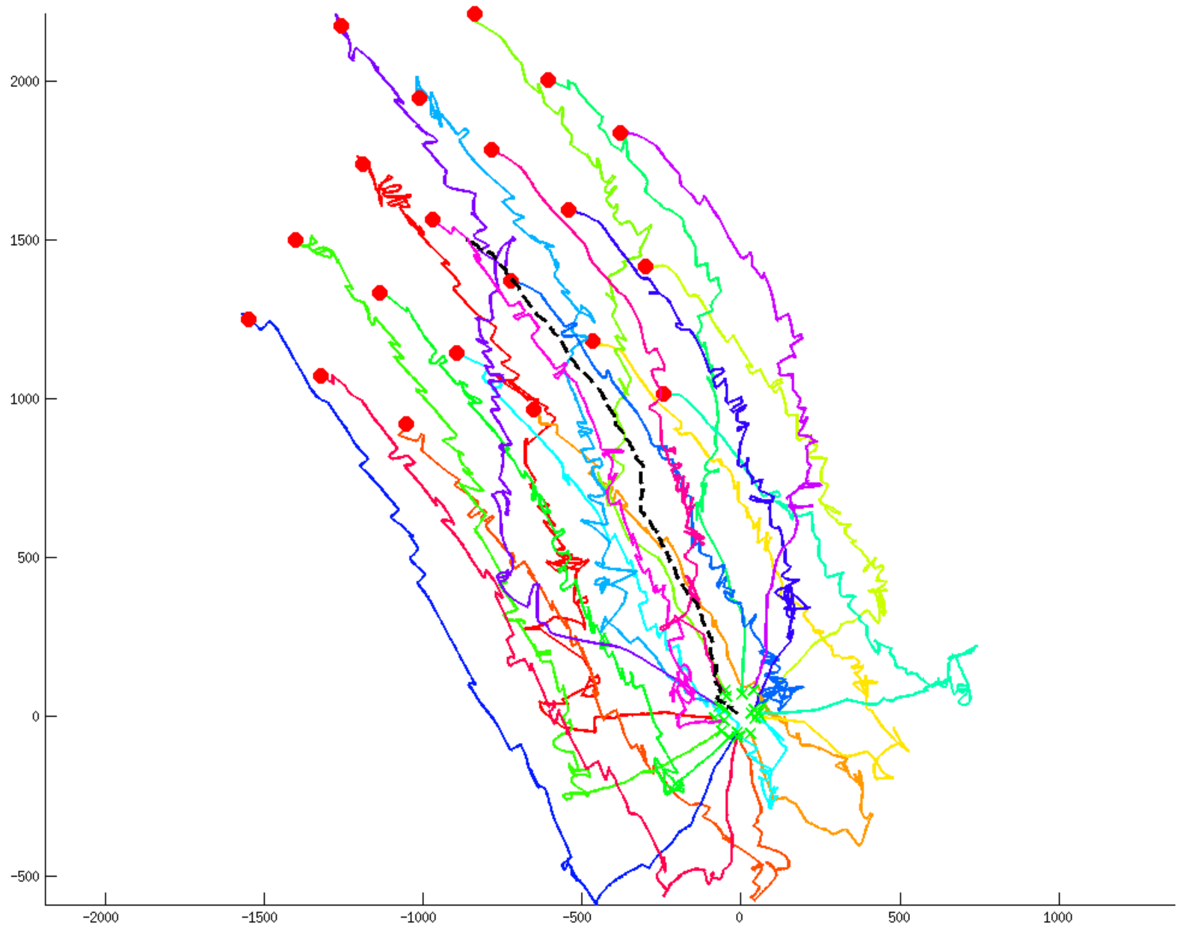
- Is it possible to dynamically assign AUVs to positions in the formation plan?:
  - Given a set of neighbour positions, we must determine which point in the plan the AUV is most suited to, using only these positions
  - This allows us to no longer require the communication of unique IDs, but still allows us to specify a desired lattice formation (unlike BHV_AttractionRepulsion)
  - My approach is brute force (next slide)

Formation Control 4 - BHV_AssignmentRegistration

Outer Loop:

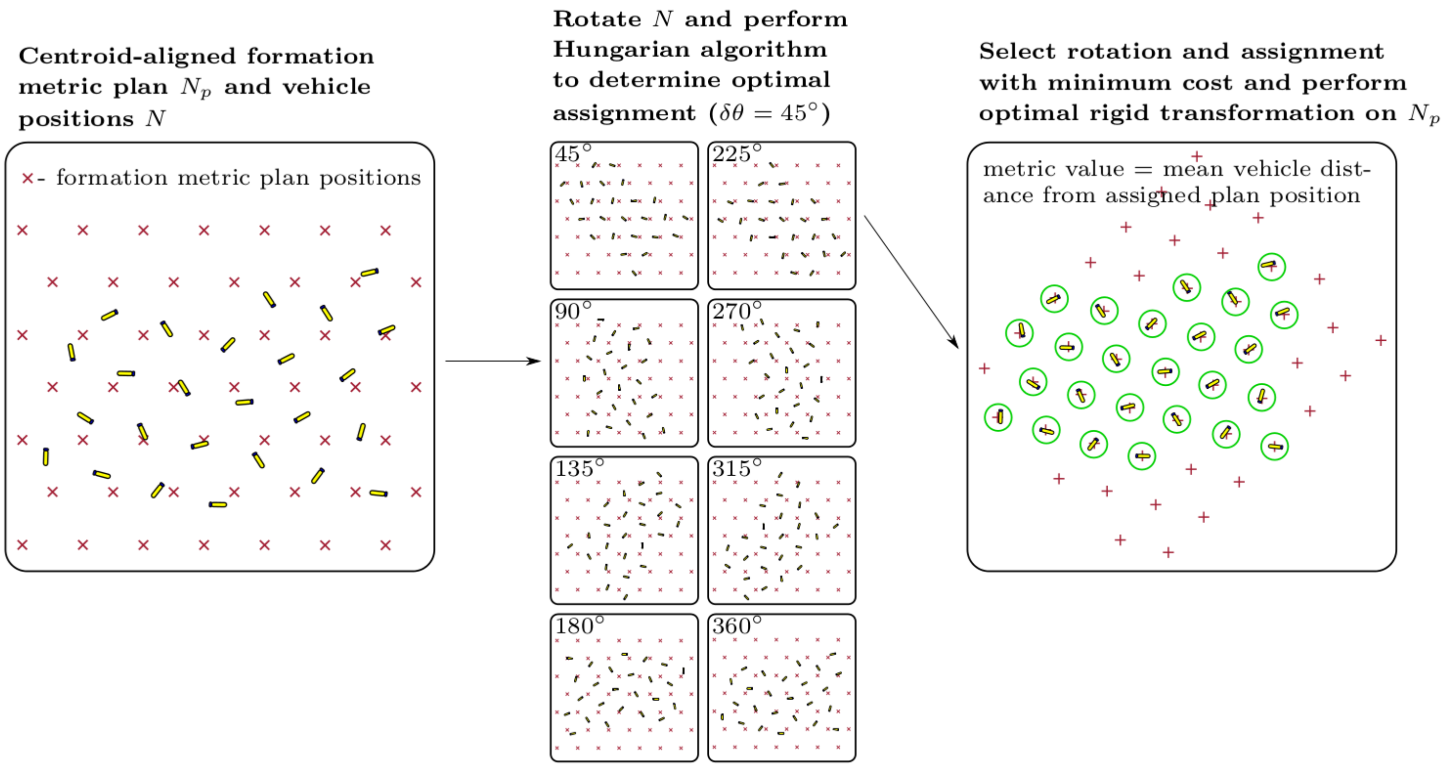
1. Given the set N of n neighbours + ownship, loop through all points in the plan
2. For each point, select it plus the n nearest points to it, giving us Np
3. Align N and Np by subtraction of centroids
4. Inner Loop:
   a) N is rotated by a specified angle delta_theta, giving N_theta
   b) Create a cost matrix specified by the distance between points in Np and N_theta, feeding this to the Hungarian algorithm to determine optimal assignment – if the cost is smaller than the previous N_theta, keep it
   c) Loop terminates after full rotation with a minimum cost with corresponding assignment and N_theta
5. Outer loop terminates after going through all points in the plan – the lowest cost point in the plan is selected along with the corresponding Np and assignment, and Np is rearranged according to this assignment
6. Finally, the optimal rigid transformation between Np and N is calculated as done in BHV_RigidNeighbourRegistration

Formation Control 4 - BHV_AssignmentRegistration



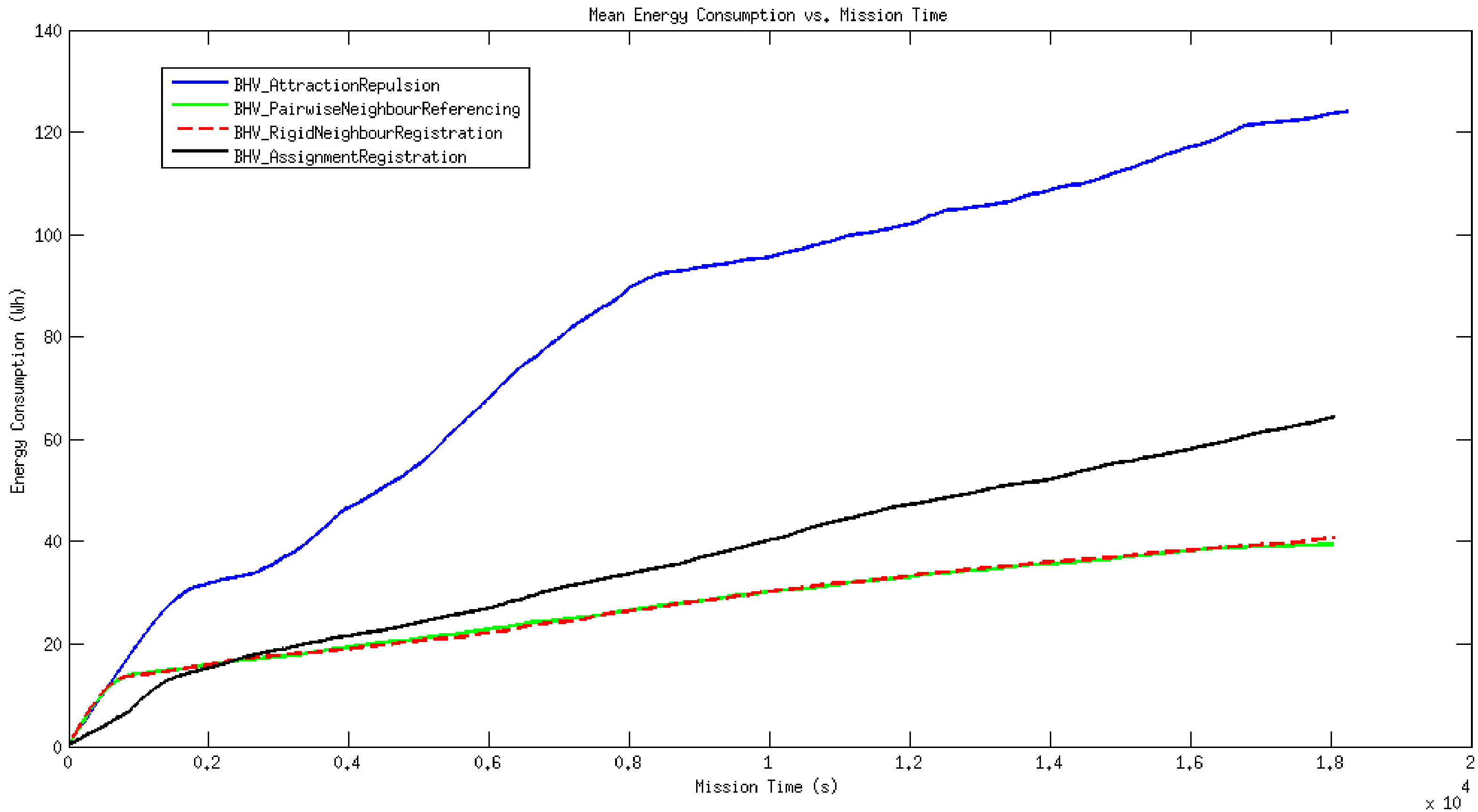
pFormationQualityMetric

- Formation quality metric used to compare how well each behaviour conforms to the desired formation:
  - Similar approach to BHV_AssignmentRegistration, but with all vehicles



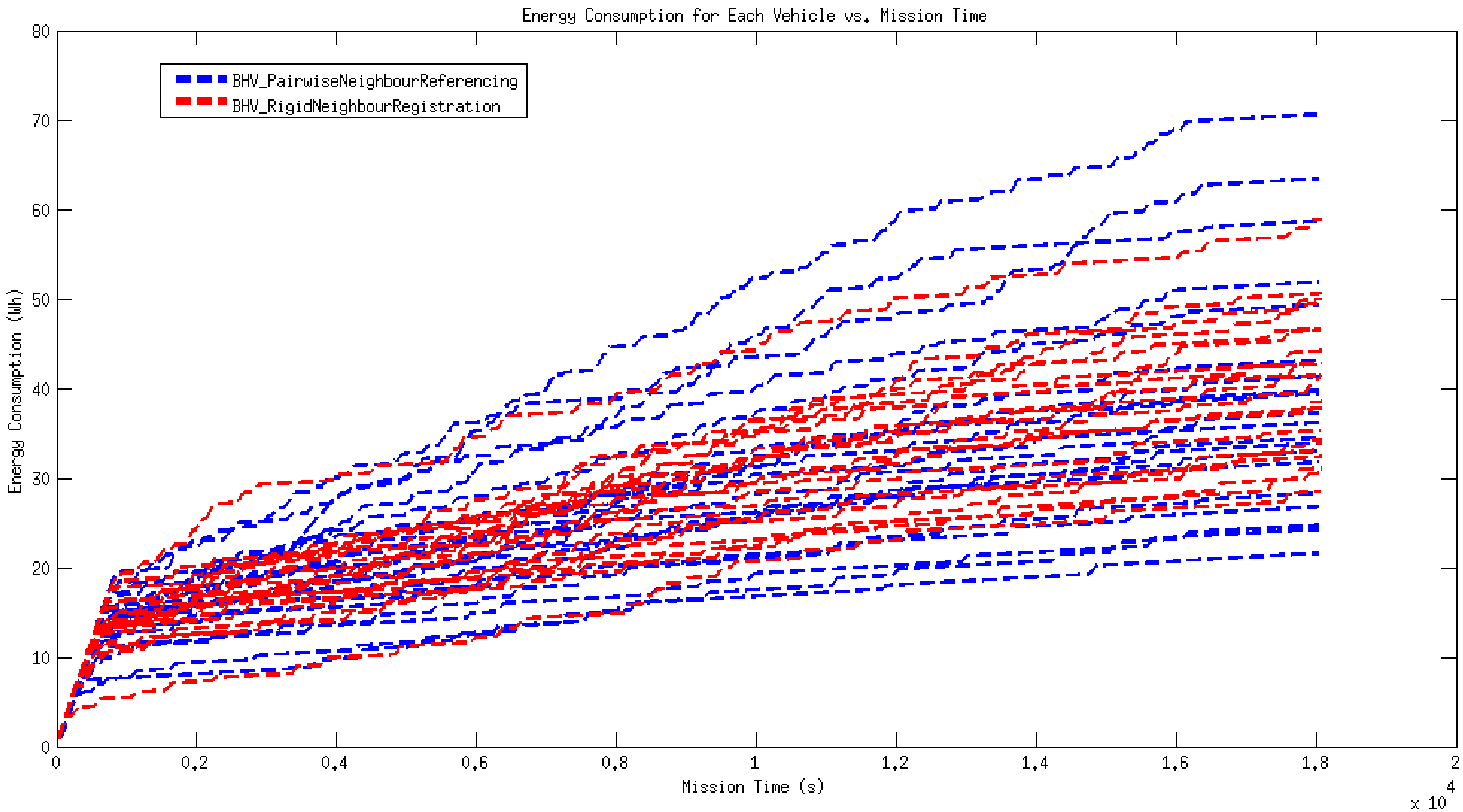
Preliminary Results – Energy Consumption

- Single trial, energy consumption (averaged over all AUVs) vs mission time



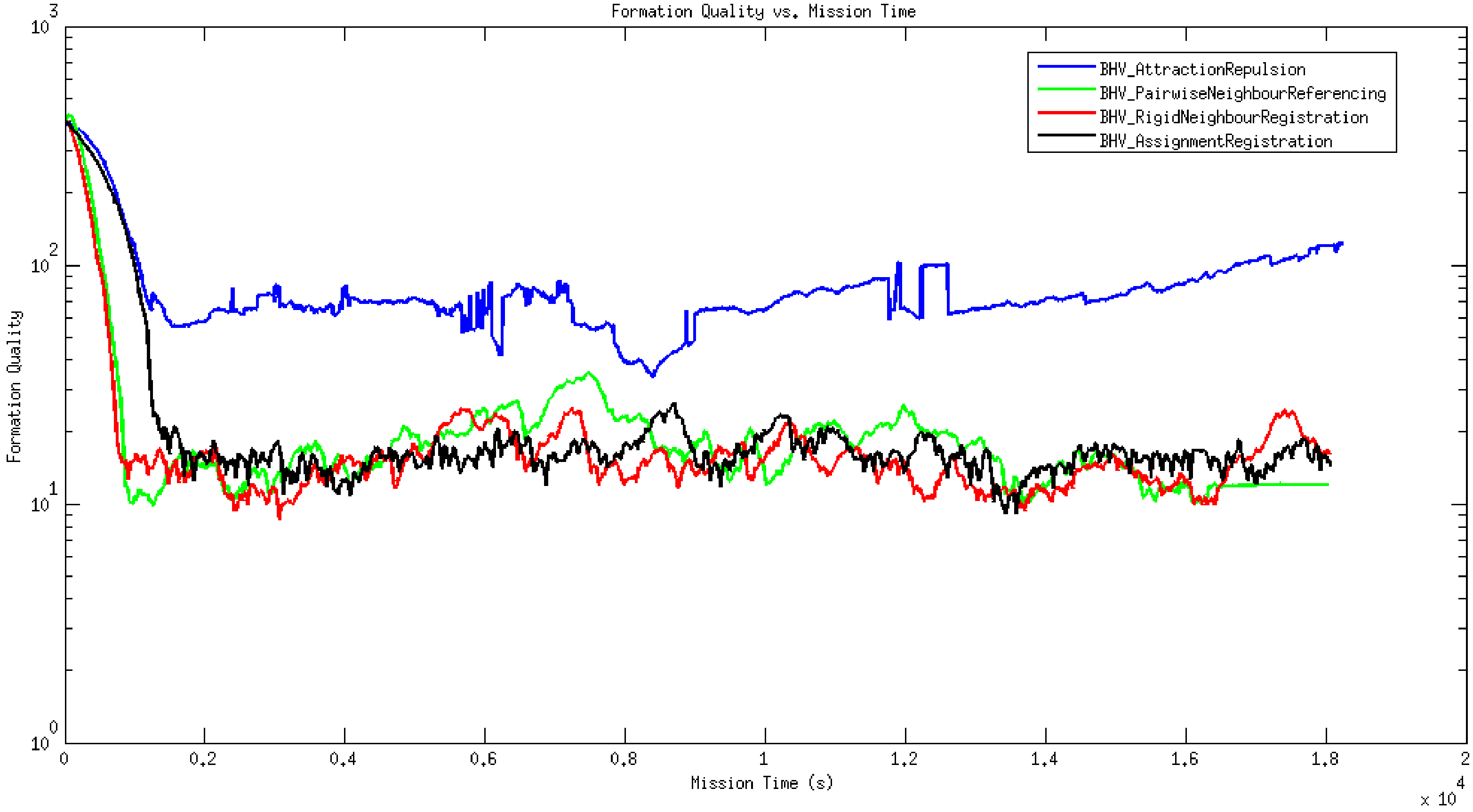
Preliminary Results – Energy Consumption

- BHV_PairwiseNeighbourReferencing vs. BHV_RigidNeighbourRegistration



Preliminary Results – Formation Quality

- Single trial, formation quality vs mission time



Conclusion and Future Work

- Four formation control behaviours + iMSEASOceanModelDirect:
  - BHV_AttractionRepulsion, BHV_PairwiseNeighbourReferencing, BHV_RigidNeighborRegistration, BHV_AssignmentRegistration
- Field Trials using simulated acoustic comms and Kingfisher ASCs
- Master's Thesis – Title: Distributed Autonomy and Formation Control of a Drifting Swarm of Autonomous Underwater Vehicles (Aug/Sep 2015)
- Proposed AUV Experimentation:
  - Range to neighbours determined using acoustic pingers, time-of-flight, and synced AUV clocks (CSAC)
  - Bearing to neighbours determined using hydrophone array or vector sensors
  - Unique IDs communicated using acoustic modem or unique pinger frequencies

Simulation Video

- 30s between simulated acoustic pings
- Gaussian noise on array:
  - 1.5m variance range
  - 5 degrees variance bearing
- 1500m/s sound speed
- Simulated acoustic max range: 550m
- Simulated currents O(10cm/s)

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