Coordination of Autonomous Underwater Vehicles for Acoustic Image Acquisition

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Outline of the Presentation

• Introduction
  – coordination among a fleet of gliders or AUVs for underwater exploration
  – imaging underwater objects: acoustic vs. optical technology

• Task allocation problem
  – find the optimum number of gliders or AUVs to complete the mission in the given time frame
  – minimize the total energy of the team of AUVs or gliders required to complete the mission
  – compare energy and time efficiency of gliders and AUVs for the same mission and time frame

• Performance evaluation

• Conclusion and future work
Underwater Sensor Networks

• Consists of:
  – Autonomous Underwater Vehicles (AUVs)

• Applications:
  – oceanographic data collection
  – pollution monitoring
  – assisted navigation
  – tactical surveillance
  – disaster prevention
  – mine reconnaissance

• These applications require coordination among AUVs
• The focus of this work is on coordination of AUVs for underwater image acquisition
Autonomous Underwater Vehicle (AUVs)

- Equipped with underwater sensors
- Act as mobile nodes for underwater acoustic sensor networks
- Find many applications on account of:
  - flexibility
  - reliance on local intelligence
- Categorized as:
  - conventional propeller-driven vehicles
Gliders

• Buoyancy-driven vehicles called gliders:
  – sample the ocean along a sawtooth trajectory
  – slower than conventional AUVs
  – permit longer-duration operations
Objectives

- The use of underwater gliders and AUVs is envisaged for ocean exploration (in particular for underwater image acquisition)
- The technique used is acoustic underwater imaging as it has numerous advantages over optical imaging
- Side scan sonar is the underwater acoustic imaging technique chosen
- Inter-glider/AUV communication is provided by using underwater acoustic waves as RF waves do not propagate over hundreds of meters
- Underwater vehicles coordinate to take images of an underwater object from different angles
- The questions this work addresses are:
  - How many gliders/AUVs are needed to take acoustic images of an object?
  - Which vehicles of the fleet should be part of the team, given the mission requirements?
  - Should we use gliders or AUVs?
Underwater Imaging: Optical

- Underwater optical imaging

- Disadvantages of underwater optical imaging
  - visibility decreases drastically in murky seawater
  - range is 1 to 3 meters (no extra light source)
  - ranges up to 10 meters can be achieved using energy-consuming lasers to light the underwater object
Underwater Imaging: Acoustic

- Underwater acoustic imaging assembly and image is as shown
- It uses sound waves for imaging
- Sound waves are transmitted and the waves reflected from object are detected to construct a 2D image

- Advantages of acoustic imaging in underwater environment
  - acoustic waves penetrate the mud and silt that causes optical turbidity
  - range is 200 to 900 meters
  - side scan sonar is the preferred underwater acoustic imaging technique
Underwater Acoustic Imaging: Azimuth Resolution

• Resolution of side scan sonar
  – Azimuth or transverse resolution
    • Ability to resolve similar objects that lie parallel to glider path
  – Range is a function of azimuth resolution

\[ R = \frac{\rho \cdot L}{k \cdot \lambda} \]

Where:
- \( R \) is the range in \( km \)
- \( \rho \) is the azimuth resolution in \( km \)
- \( k \) is the receiver constant
- \( \lambda \) is the wavelength in \( km \)
Underwater Acoustic Imaging: Range Resolution

- Range or across track resolution
  - minimum distance between two objects that lie perpendicular to vehicle path appear separate
  - range resolution is given by the width of the transmitted sonar pulse

\[ \Delta = \frac{c \cdot \tau}{2} \]

- \( \Delta \) is the range resolution
- \( c \) is the speed of sound in water 1500 m/s
- \( \tau \) is the transmitted pulse width
Basic Model Assumptions

• Mathematical model is defined in accordance with:
  – A virtual sphere known as the object sphere of radius $r$ [m] is assumed around the target object.
  – For formation of constellation of gliders or AUVs a concentric virtual sphere named constellation sphere of radius $R$ is assumed around the object such that $R > r$.
  – The radius of the constellation sphere is a function of the range resolution of the acoustic imaging system used, which provides us with the minimum and maximum value of $R$. 

![Diagram showing object and constellation spheres with glider vertices and polyhedron.]
Basic Model Assumptions

• All gliders or AUVs in the constellation form a symmetric polyhedral structure (constellation polyhedron)
  – All the points of the polyhedron lie on the constellation sphere
• Each vehicle is assigned a unique point, optimum position on the constellation sphere, so as to avoid collision between two gliders or AUVs
• Vehicles start scanning the object from these positions
  – AUVs/gliders are constantly moving (side scan sonar imaging can be done only when vehicles are in motion)
  – Vehicles move in fixed pattern
Optimization Task Allocation Problem

• Selection of the optimum number of AUVs/gliders to:
  – minimize the energy required by the team of vehicles to travel towards the optimum positions on the constellation polyhedron
  – meet the time bound $\delta$ to take the image (including time for movement and scanning)

• The problem is formulated as a Mixed Integer Non-linear Program (MINLP)

• Working assumptions:
  – vehicles are already deployed in the ocean
  – mission details (including 3D coordinates of object) are received from a surface station or object information is already gathered from classification and ranging
  – each vehicle has information about relative position of other vehicles and distance from the target object
Multi-glider Task Allocation Problem

Given: \([\text{Pos}_g^i, C_o, G, r, P^M, P^\Omega, R_{\text{min}}, R_{\text{max}}, \delta, V_g, T_{\text{on}}, C_n]\)

Find: \(\text{Pos}_g^f, X_f^*, R^* \in [R_{\text{min}}, R_{\text{max}}]\)

Minimize: \(\sum_{g \in G} [E^M + E^\Omega] \cdot X_g\)

Subject to:

\[
E^M_g = C_n \cdot \sqrt{(x^f - x_o)^2 + (y^f - y_o)^2} \cdot p^M \cdot T_{\text{on}}
\]

• This constraint determines the total energy required to operate the buoyancy engine

\[
E^\Omega_g = p^\Omega \cdot T^\Omega_g
\]

• This constraint determines the energy required to capture images of the whole object if the glider were alone on the mission
Multi-glider Task Allocation Problem

\[ T^M_g = \frac{\sqrt{(x_f^g - x_o^g)^2 + (y_f^g - y_o^g)^2}}{V_g} \]

- This constraint determines the time the glider will take to reach the target object at a horizontal velocity \( V_g \).

\[ T^\Omega_g = \frac{2 \cdot \pi \cdot R}{V_g} \]

- This constraint determines the time the glider would take to acquire the images of the whole object if it were alone on the mission.
  - This is the time the glider would need to acquire the images as it hops from one \( \text{optimum position} \) to another on the \( \text{constellation polyhedron} \).
Multi-glider Task Allocation Problem

\[ T_{Total} = 1 + \sum_{g=1}^{\left| G \right|} \left( \frac{T_g^M}{T_g^\Omega} \right) \cdot X_g \leq \delta \]

This constraint determines the total time for the mission and assures that it will be less than the time bound \( \delta \):

- It takes into consideration the time taken by each glider to travel towards the object as well as time to take images of the whole object by a single glider.
Multi-glider Task Allocation Problem

\[(x_f^g - x_o)^2 + (y_f^g - y_o)^2 + (z_f^g - z_o)^2 \cdot X_g = R^2\]

- This constraint determines the distance between the center of the object sphere and the optimum position of the gliders.

\[\sum_{g \in G} X_g \geq 1\]

- This constraint assures that at least one glider be selected for the mission.

\[\sum_{g \in G} X_g \leq |G|\]

- This constraint assures that the number of gliders chosen for the mission be less than or equal to the total gliders available.
Multi-AUV Task Allocation Problem

- The problem formulation for propeller driven AUVs is similar to that of gliders.
- The only difference is that AUVs are able to change the velocity according to time bound but at the cost of extra energy given by,

\[ E^M_a = \left[ \zeta \cdot V \gamma_a + P^M_{\text{min}} \right] \cdot T^M_a \]

- This constraint is very different from that for gliders as most of the energy of AUVs is spent for keeping their propellers on while traveling towards the object.
Performance Evaluation

- Energy comparison based on time bound $\delta$
- The MINLP was formulated as a AMPL problem and solved using the MINOS optimization server
- The parameter values for gliders are set as follows
  - Power to operate the buoyancy engine is 90 Watts
  - Power required by acoustic assembly is 45 Watts
  - Velocity of glider is 1.4 km/hr
  - $C_n$ has a value 4
  - $T_{\text{on}}$ has a value 0.015 hr
Performance Evaluation: Energy Comparison based on time bound $\delta$

- As the time bound $\delta$ increases the energy for the team of AUVs and gliders differs
  - The energy of a team of gliders is much less than for AUVs as time bound increases
- AUVs are time efficient while the gliders are energy efficient
- There is a trade-off between time and energy efficiency
  - If the mission is time critical, a team of AUVs is preferred
  - If the mission is energy critical with large time bound a team of gliders is preferred
Performance Evaluation: Energy comparison based on number of Gliders and AUVs in the team

- It is observed that as $\delta$ decreases the number of gliders required in the team increases, while that of AUVs is somewhat constant
- Gliders are slow as compared to AUVs and for some time bound $\delta$ it is impossible for any number of gliders to complete the mission
  - Because of glider constant velocities, there is less flexibility in deciding the number of gliders composing a team
  - In other words, too few gliders cannot complete the mission
Performance Evaluation: Localized Nature of the Problem

- The distance from which gliders are selected to form the optimal team is almost constant as the team size increases (gliders are movement-constrained).
- Conversely, the distance from which AUVs are chosen as the team size increases also increases to cover the entire deployment region.
- The problem of optimal team selection for vehicles is localized in nature because:
  - When ocean currents are not considered, the optimum team is always composed of vehicles in the proximity of the target object.
Conclusions and Future Work

• Centralized optimization always provides the best solution
• However, because the problem is localized, even if we compute a localized sub-optimal heuristic, we will get a solution nearly as good as the centralized one
• Finally we showed that it exists a tradeoff between time and energy
  – In missions with large delay bounds, we can use gliders and consume less energy
  – In missions with short delay bounds, we need to use AUVs and pay the price of higher energy

• As future work, we will:
  – find the optimum trajectory for the vehicles to reach the constellation (swarming approaches)
  – develop communication protocols to support the distributed coordination framework proposed