Baseline Replication and Analysis of MLCCST for Line-of-Sight Connectivity in Multi-Robot Systems

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***Abstract*—Maintaining reliable communication and coordination among underwater autonomous vehicles (AUVs) is a fundamental challenge due to the limitations of acoustic communication, dynamic marine environments, and the presence of physical obstructions. This work presents a partial replication of the "Minimum Line-of-Sight Connectivity Constraint Spanning Tree (MLCCST)" framework in a simulated underwater environment using MATLAB. The system models AUVs as point robots operating under strict Line-of-Sight (LOS) communication constraints, simulating real-time relay formation and decentralized coordination. Robots are assigned to different task zones while maintaining global and subgroup connectivity through dynamically generated MLCCSTs. Upon reaching the target area, a subset of AUVs forms circular formations, while others act as relays to preserve LOS-based communication chains. Although the simulation successfully models dynamic tree formation and adaptive relay allocation, the implementation of Control Barrier Functions (CBFs) for obstacle avoidance remains limited, especially in cluttered environments. Future work aims to integrate Control Lyapunov Functions (CLFs) alongside CBFs to enable dynamic expansion and contraction of the connectivity tree based on mission requirements, while also transitioning toward realistic AUV dynamics in a physics-based environment such as Gazebo or Simulink.**

***Index Terms*—Underwater Autonomous Vehicles (AUVs), Line-of-Sight (LOS) Connectivity, Control Barrier Functions (CBFs), Control Lyapunov Functions (CLFs), Multi-Robot Coordination, Minimum Spanning Tree (MST), Relay Allocation, Connectivity Maintenance, Obstacle Avoidance, Underwater Communication Networks**

I. Introduction

Autonomous Underwater Vehicles (AUVs) have become indispensable in oceanographic research, environmental monitoring, and underwater exploration due to their ability to operate in challenging and hazardous environments. As mission complexities increase, the deployment of multiple AUVs in coordinated formations offers advantages such as improved coverage, redundancy, and efficiency. However, achieving effective coordination among multiple AUVs presents significant challenges, particularly in maintaining reliable communication and ensuring collision-free operations in dynamic underwater environments. Underwater communication relies primarily on acoustic signals, which are restricted by limited bandwidth, high latency, and susceptibility to environmental interference. These limitations require strategies that ensure robust communication links among AUVs. An effective approach is maintaining line of sight (LOS) connectivity, which facilitates direct communication pathways and reduces the likelihood of signal degradation. Recent studies have explored decentralized path planning methods that explicitly avoid situations where lack of visibility among agents could lead to unsafe conditions, thus emphasizing the importance of LOS maintenance in multi-robot systems [1]. To address the challenges of LOS connectivity and coordinated control, the Minimum Line-of-Sight Connectivity Constraint Spanning Tree (MLCCST) algorithm has been proposed. This algorithm constructs a spanning tree that minimally constrains the original multirobot behaviors while ensuring global and subgroup LOS connectivity. By formulating the problem as bilevel optimization and using control barrier functions (CBFs), MLCCST enables real-time reconfiguration and maintenance of connectivity for AUVs operating in complex environments [2]. In this work, we implement and validate the MLCCST algorithm within a MATLAB-based simulation environment, modeling AUVs as point-mass robots. The simulation assigns robots to specific target regions, dynamically designates relay nodes to maintain tree-based connectivity, and uses CBFs to enforce safety, obstacle avoidance, and LOS constraints. Although the framework demonstrates promising results in terms of goal convergence and network formation, challenges remain to achieve robust obstacle avoidance using CBFs, particularly in cluttered underwater settings. Future work will focus on integrating Control Lyapunov Functions (CLFs) alongside CBFs to facilitate adaptive goal convergence and dynamic manipulation of the connectivity structure. This integration aims to enable the expansion and retraction of the AUV relay tree in response to evolving mission objectives and environmental conditions, thereby enhancing the flexibility and effectiveness of multi-AUV operations.

II. System Model and Problem Formulation

In this work, we consider a team of autonomous underwater vehicles (AUVs) operating in a bounded two-dimensional workspace populated with static polyhedral obstacles. The AUV team is tasked with reaching spatially distributed target areas while maintaining global and subgroup Line-of-Sight (LOS) connectivity under obstacle-induced visibility constraints.

A. Robot Dynamics

We model each AUV as a single-integrator point-mass robot with first-order kinematics, defined as:

$$\dot{x}_i = u_i, \quad x_i \in \mathbb{R}^2, \quad u_i \in \mathbb{R}^2 \tag{1}$$

where x_i and u_i and denote the position and control input of robot i, respectively. This simplification is reasonable during high-level coordination and allows easy integration with control barrier functions (CBFs) for safety and connectivity constraints.

B. Environment and Communication Model

The underwater environment is modeled as a continuous free space interspersed with static obstacles $C_{\text{obs}} \subset \mathbb{R}^2$ Each obstacle is represented as a rectangular polygon for simplicity. Robots can only communicate if they satisfy the following LOS-based criteria:

1) Proximity Constraint: he Euclidean distance between robots i and j must be less than the communication radius R_c.

2) Occlusion-Free Visibility: The line segment between x_i and x_j must not intersect any obstacle in C_{obs}.

The above conditions define the LOS communication graph $G_{\text{LOS}} = (V, E_{\text{LOS}})$, where V is the set of all robots and $E_{\text{LOS}} \subseteq V \times V$ contains undirected edges representing feasible communication links.

C. Task Allocation and Control Objective

Each AUV is assigned one of four predefined task areas. The mission objective is two-fold:

1) Goal Achievement: At least one robot from each task group must reach its designated goal area.

2) LOS Maintenance: A connected communication structure must be preserved among all robots using LOS constraints.

To facilitate scalable communication, we seek to maintain the minimum required number of communication links via a Minimum Line-of-Sight Connectivity Constraint Spanning Tree (MLCCST), while guiding the swarm in a tree-like structure toward the task areas.

D. Control Barrier Functions (CBFs)

We use control barrier functions to define safe and admissible control inputs under the following constraints:

1) Inter-Robot Safety:

$$h_{ij}^s(x) = \|x_i - x_j\|^2 - R_s^2 \geq 0 \tag{2}$$

2) Robot-Obstacle Avoidance:

$$h_{io}^{\text{obs}}(x) = \|x_i - x_o^{\text{obs}}\|^2 - R_{\text{obs}}^2 \geq 0 \tag{3}$$

3) Connectivity Maintenance:

$$h_{ij}^c(x) = R_c^2 - \|x_i - x_j\|^2 \geq 0 \tag{4}$$

4) LOS Connectivity (Ellipsoidal Approximation): For every edge $(i, j) \in E_{\text{LOS}}$, we define an ellipsoidal region enclosing the segment from x_i to x_j and ensure obstacles do not lie within this region. The control constraint becomes:

$$\dot{h}_{ij,o}^{\text{los}}(x, u) + \gamma h_{ij,o}^{\text{los}}(x) \geq 0, \quad \forall o \tag{5}$$

E. Optimization-Based Controller

At each timestep, the control inputs are computed by solving the following Quadratic Program (QP):

$$u^* = \arg\min_u \sum_{i=1}^{N} \|u_i - \hat{u}_i\|^2 \tag{6}$$

Subject to:

$$u \in \mathcal{B}_s(x) \cap \mathcal{B}_{\text{obs}}(x) \cap \mathcal{B}_{\text{LOS}}(x) \tag{7}$$

$$\|u_i\| \leq u_{\max} \quad \forall i \tag{8}$$

Here, $\hat{u}_i$ represents the nominal task-following controller for robot i. The barrier sets ensure inter-robot safety, obstacle avoidance, and connectivity.

III. Implementation

To evaluate the proposed MLCCST-based coordination strategy, we implemented a MATLAB-based simulation environment that models the motion of a team of AUVs operating in a bounded 2D underwater environment. The key components of the implementation include robot spawning, LOS graph construction, control barrier formulation, and QP-based motion planning.

A. Simulation Setup

The simulation workspace is defined as a 10×10 meter area containing multiple rectangular static obstacles representing submerged debris or seabed features. Four task zones are defined at the corners of the map, representing region-specific exploration or surveillance targets. A group of $N = 40$ robots is deployed from a randomly selected task area, with each robot assigned a goal corresponding to one of the four task zones.

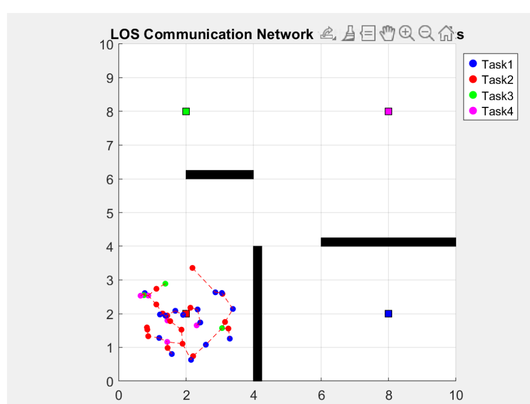

Fig. 1. Simulation workspace with obstacles and task zones.

B. Robot Control and Connectivity

Robots are modeled using single-integrator dynamics, and their control input is derived by solving a constrained QP at every timestep. The control objectives are to:

- Guide each robot towards its goal area.
- Maintain both global and subgroup LOS connectivity.
- Ensure collision avoidance with other robots and static obstacles.

To ensure LOS-aware communication, a line-of-sight communication graph is dynamically computed using a geometric occlusion check based on ray intersection with polygonal obstacles. A Minimum Volume Enclosing Ellipsoid (MVEE) is also used to approximate and enforce obstacle-free communication regions.

C. MLCCST Construction

For each simulation step, a Minimum Line-of-Sight Connectivity Constraint Spanning Tree (MLCCST) is generated using a weight-assignment scheme:

- Edges in the LOS graph are assigned weights based on how close they are to violating safety, connectivity, or LOS constraints.
- A unique weight-penalization strategy is applied to favor edges within the same task group and discourage unnecessary cross-group connections.

The final spanning tree ensures minimum constraint violation while preserving both global and subgroup LOS connectivity.

Algorithm 1 MLCCST Algorithm

Input: $\mathbf{x}$ - the current states (positions) of the robots, $\hat{\mathbf{u}}$ - the nominal task-related multi-robot controller, C_{obs} - the occupied space of the obstacles

Output: The desired minimally modified controller $\mathbf{u}^* \in \mathbb{R}^{dN}$

function MLCCST($\mathbf{x}, \hat{\mathbf{u}}, C_{\text{obs}}$)
  for Each time step **do**
    for All edges $(v_i, v_j) \in \mathcal{E}^{\text{los}}$ of current LOS communication graph $\mathcal{G}^{\text{los}} = (\mathcal{V}, \mathcal{E}^{\text{los}})$ **do**
      Weight assignment: $\mathcal{W}'_{i,j} \leftarrow -w'_{i,j}$
    end for
    Get new weighted graph $\mathcal{G}^{\text{los}'} = (\mathcal{V}, \mathcal{E}^{\text{los}'}, \mathcal{W}')$
    Solve $\bar{\mathcal{T}}_w^{\text{los}'} = \arg\min_{\mathcal{T}^{\text{los}'}} \sum_{(v_i,v_j)\in\mathcal{E}^{\mathcal{T}}} -w'_{i,j}$
      by standard MST algorithm: $\bar{\mathcal{T}}_w^{\text{los}'} \leftarrow \text{MST}(\mathcal{G}^{\text{los}'})$
    return $\mathbf{u}^* = \arg\min \sum_{i=1}^{N} \|\mathbf{u}_i - \hat{\mathbf{u}}_i\|^2$
      where $\mathbf{u} \in \mathcal{B}^s(\mathbf{x}) \cap \mathcal{B}^{\text{obs}}(\mathbf{x}, \mathbf{x}^{\text{obs}}) \cap \mathcal{B}^{\text{los}}(\mathbf{x}, \bar{\mathcal{T}}_w^{\text{los}'})$
      and $\|\mathbf{u}_i\| \leq u_{\max}, \ \forall i = 1, \ldots, N$
  end for
end function=0

D. Dynamic Relay Allocation and Goal Structuring

To prevent all robots from converging into a single point at the goal, a dynamic relay assignment mechanism is used:

- Robots close to their goal location (within a predefined radius) form a circular formation around the task area.
- Remaining robots dynamically allocate themselves as relays based on the LOS edge lengths. If an edge exceeds a threshold (e.g., 0.5 m), the robot is forced to act as a relay and hold position to maintain connectivity.

This results in a tree-like relay structure extending from the start zone to the goal zone.

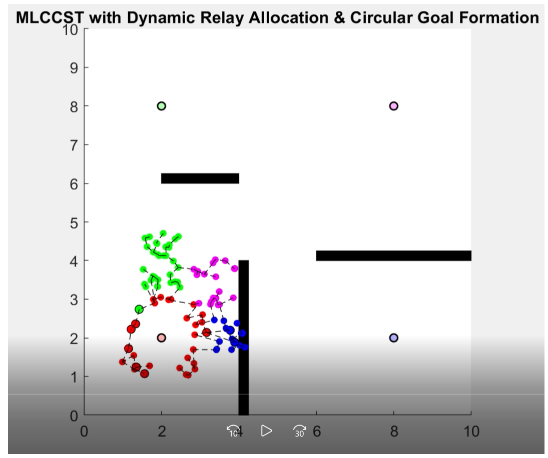

Fig. 2. Relay allocation and goal-structured formation.

E. Visualization

The simulation outputs include:

- Real-time robot trajectories with color-coded task affiliations.
- Time-varying LOS connectivity graphs rendered as dashed lines.
- Distinction between active robots and relay nodes through marker size and edge highlights.

The framework ensures all motion constraints are respected while providing a flexible and interpretable connectivity-aware behavior.

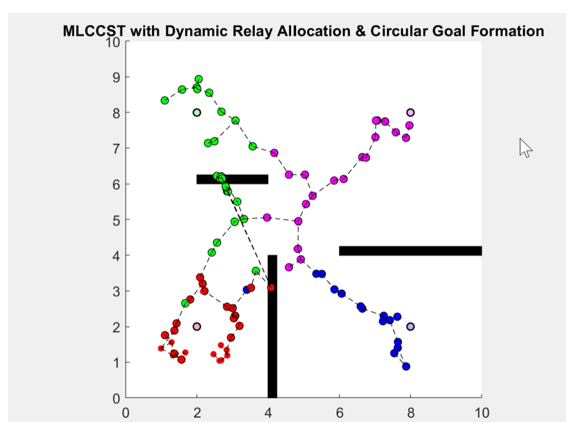

Fig. 3. Final simulation output showing trajectories, task zones, and relay nodes.

IV. Results and Discussion

The proposed MLCCST-based control framework was evaluated in multiple simulated underwater scenarios using a team of 100 autonomous underwater vehicles (AUVs). Each robot was initialized from a single task area and assigned a random goal among four defined task zones. The simulations demonstrated the framework's ability to maintain global and subgroup LOS connectivity, while guiding robots toward their goals without violating the communication or safety constraints.

The resulting formations exhibited a tree-like structure, where robots autonomously positioned themselves to relay communication and maintain LOS with both peers and target areas. This behavior emerged organically from the composition of Control Barrier Functions (CBFs), without the need for hard-coded coordination logic. The MLCCST algorithm ensured minimal edge retention for connectivity, reducing computational complexity and allowing scalable robot deployment.

Despite these successes, the simulations also revealed some limitations:

- CBF-based obstacle avoidance was less robust in complex or tight environments. Some robots exhibited near-grazing behavior around obstacle edges or became motion-constrained due to conflicting CBF terms.
- In certain cases, excessive convergence was observed at the goal area, causing dense clustering of robots before they spread out into the circular formation.
- Relay nodes occasionally repositioned inefficiently when multiple LOS constraints were simultaneously violated, suggesting the need for more adaptive prioritization.

Overall, the results validate the effectiveness of the MLCCST framework in maintaining connectivity and goal-directed motion in LOS-constrained environments, while highlighting the need for improved multi-constraint resolution strategies.

V. Conclusion and Future Work

This work implements a Control Barrier Function (CBF)-based framework for maintaining Line-of-Sight (LOS) connectivity in a multi-robot underwater environment using the Minimum Line-of-Sight Connectivity Constraint Spanning Tree (MLCCST) approach. AUVs (Autonomous Underwater Vehicles) begin from a common location and are distributed to perform goal-oriented movement while maintaining group-level and global connectivity in the presence of obstacles and limited communication range.

The simulation, implemented in MATLAB, validates key aspects of the theoretical model—particularly the adaptive assignment of relay robots and the tree-like formation during motion. Robots maintain connectivity using MLCCST, avoid communication loss through relays, and demonstrate self-organization near goal areas into circular formations.

However, some aspects of the theoretical baseline remain challenging in simulation:

- The CBF-based obstacle avoidance component struggles near sharp corners or in densely clustered environments, occasionally resulting in undesired proximity to obstacles.
- All robots from a task group tend to converge to the same goal location, which may cause redundancy and limit the system's relay diversity.

To address these limitations and expand the framework, the following future directions are proposed:

1) Improved Obstacle Avoidance CBFs: Strengthening the CBF formulation to provide more conservative, robust obstacle avoidance in tight spaces or around complex obstacle boundaries.

2) Dynamic Tree Growth and Shrinkage: Incorporating Control Lyapunov Functions (CLFs) alongside CBFs to enable controlled expansion or retraction of the communication tree structure as needed, depending on mission demands or spatial coverage requirements.

3) Adaptive Goal Reallocation: Dynamically reassign robots within the same subgroup for optimized task execution and more efficient relay distribution.

4) Integration with Realistic Underwater Simulation Platforms: Extending this framework to ROS 2 and Gazebo with realistic hydrodynamic models, acoustic communication delays, and environmental disturbances.

By pursuing these enhancements, the system can be made more flexible, robust, and scalable for real-world AUV coordination tasks such as seabed mapping, surveillance, or underwater infrastructure inspection.

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