Combined Task and Motion Planning for AUVs

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***Abstract*— This paper builds on recent work towards sampling based motion planning and task planning using linear temporal logic (LTL) in an effort to increase the planning capabilities of autonomous underwater vehicles (AUVS). To generate low-cost paths that execute multiple coverage tasks, the planner generates a discrete abstraction that considers the workspace of the AUV and a mission specification expressed in LTL. Sampling-based motion planning is used to generate a motion tree which is then mapped to states in the LTL mission specification corresponding to a determinisstice finite automaton (DFA) inducing an equivalence class. Heuristics imposed over the discrete abstraction are employed in order to estimate the feasibilty of expanding the motion tree from an equivalence class to a new automaton state. Results in this paper provide an overview of existing work.**

I. Introduction

Mission planning for autonomous underwater vehicles (AUVs) requires the ability to reason over both the continuous and discrete domain. Complex AUV missions incorporating inspection tasks, perpetual surveillance, maneuvering through restrictive environments, etc. call for a planner with capabilities indicative to both the robotics and artificial intelligence (AI) communities. Complexity arises in the temporal scope of the mission, traversing different areas and sampling data uses considerable amounts of energy when having to combat time varying ocean currents that may impede the motion of the vehicle. While considerable amounts of work has been performed in researching optimal paths for AUVs in time varying ocean currents, there has been little work done in planning low-cost paths for AUVs while considering multiple objectives. Recent works involving AI planning with AUVs has included constraint-based temporal planning [1] and planning using PDDL domain descriptions for AUVs [2] where plans are executed and modified in real-time.

The objective of this project is to develop a planning framework that uses a model of the world including time-varying ocean currents to quickly plan and re-plan feasible paths for the AUV that execute the high-level mission described by a user efficiently. Breaking down the mission specification as a series of discrete tasks using linear temporal logic (LTL) allows for the planning algorithm to take the ordering of tasks away from the user, removing potential user error as well as the inefficient ordering of tasks. LTL combines propositions, logical ($\wedge$ and, $\vee$ or, $\neg$ not) and temporal ($\bigcirc$ next, $\lozenge$ eventually, $\square$ always, $\cup$ until) connectives in order to describe complicated tasks as a series of discrete actions. As an example, the task of sampling data from multiple regions while remaining collision free can be described as

$$\square \pi_{safe} \wedge \lozenge \pi_{A_1} \wedge \ldots \wedge \lozenge \pi_{A_n} \tag{1}$$

where π_{safe} represents a propositional variable that describes a mission element. In this example, π_{safe} represents the proposition "*No Collisions*" which is preceded by the "*always*" operator, i.e. "*always remain collision free*". π_{safe} is joined using the logical operator "*and*" with other propositions π_{A_N}, "*sample area A_N*", which are preceded with the "*eventually*" operator. The result of this LTL specification is the sentence "*Always remain safe and eventually sample area A_1 and … eventually sample area A_N*".

II. Method

The work in this project builds off of prior work towards a synergistic combination of layers of planning (Syclop) [3]. The approach combines sampling based motion planning with discerete planning using LTL, treating the planning problem as a probabilistic search over a hybrid continuous and discrete space. Planning with LTL provides a framework to handle task ordering while guiding the motion search through high level objectives. Specifically, the workspace of the AUV is decomposed into discrete regions using a probabilisti roadmap (PRM). The physical adjacency between each region is captured in the edges of a graph whose verticies correspond to the decomposed regions. The regions of the graph are then labeled with propositions from the LTL specification that are satisifed within eah region. The discrete abstraction is then defined as $\mathcal{A} \times D$. Abstract states $\langle z, r\rangle$ are composed of the automaton states $z \in Z$ and decomposition regions $r \in R$. Once the abstration is constructed, heuristic costs that take into account the distances between an accepting automaton state and an abstract state $\langle z, r\rangle$ are computed using Dijkstra's single-source shortest-path algorithm where the weight is defined as the distance between two verticies of the abstraction.

Sampling-based motion planners are then invoked in order to create the motion tree, $\mathcal{T}$. Starting at the root of the tree, the corresponding abstract state of verticies in $\mathcal{T}$ can be determined by mapping which regions r the tree passes through and what automaton states z are visited. This induces an equivalence class $\Gamma_{\langle z,r\rangle}$ consisting of all the vertices that map to $\langle z, r\rangle$.

The motion tree $\mathcal{T}$ is expanded from $\Gamma_{\langle z,r\rangle}$ by first selecting a vertex from $\Gamma_{\langle z,r\rangle}$ and then extending a collison-free and dynamically feasible trajectory starting from the

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state associated with the vertex v. The selection of v is designed to promote growth towards new automotaun states by selecting points to expand the motion tree using regions in $D = (R, E)$ that have yet to be visited. The vertex v is selected by finding the nearest vertex to the newly sampled point.

III. Experiments and Results

The approach is tested on a simulated environment using the MOOS-IvP [4] framework in order to obtain an accurate AUV simulator. MOOS-IvP uses a second order system to simulate the dynamics of an AUV using heading, depth, and speed as control inputs. The ocean floor is a simulated map created by adding random peaks and valleys as shown in Fig. 2 . Ocean currents are modeled using the HYbrid Ocean Coordinate Model (HYCOM) [5] in order to generate realistic time-dependent ocean currents, see Fig. 1. These experiment conditions provide a challenging environment due to changes in topography and ocean current. Dynamic constraints are imposed on the AUV such that it must track a certain distance from the ocean floor. Furthermore, in the experiments different LTL specifications are considered, the first being a coverage mission that requires the AUV to visit each area of itnerest:

$$\phi_1 = \bigwedge_{i=1}^{n} \Diamond \pi_{A_i}.$$

where an area A_i is defined as a box, placed at random inside the test environment. Here the mission specificiation leaves it up to the planner to decidce the appropriate ordering of areas to visit. The second mission is a covereage mission with a pre-defined sequence that the AUV most follow:

$$\phi_2 = \beta \cup (\pi_{A_1} \wedge ((\pi_{A_1} \vee \beta) \cup (\pi_{A_2} \wedge (\ldots (\pi_{A_{n-1}} \vee \beta) \cup \pi_{A_n})))),$$

$$\text{where } \beta = \wedge_{i=1}^{n} \neg \pi_{A_i}$$

Fig. 3 provides a summary of the results when varying the number of areas of interest in the misssion specifications. The speedup in computational time is due to the use of equivalence classes that capture the progress made by the planner which then informs heuristics defined over the discrete abstraction. Further speedups can be attributed to the use of PRMs in the construction of the workspace decomposition.

IV. Discussion

This paper focused on mission and motion-planning for AUVs and how to enhance the capabilities of current AUV control systems by taking into account operations as expressed by LTL specifications. The proposed approach is a planner which considers a hybrid discrete and continuous space when planning feasible low-cost motion trajectories that execute the high level mission specification described by the user by combining the expantion of a motion tree with a discrete search through an automaton representing an LTL specification. The project is currently ongoing and future research includes moving the planner into a replanning framework for use on a system in real-time.

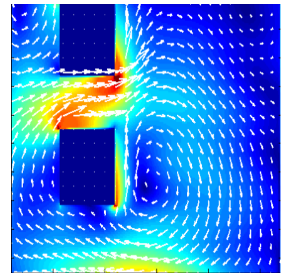


Fig. 1. An example of ocean currents generated by HYCOM in a 2-D map with two obstacles. Arrows are the direction of current velocity and the color indicates magnitude.

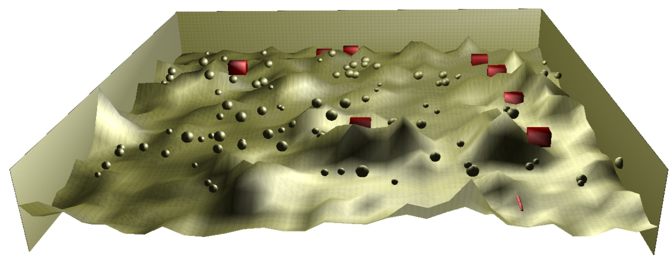
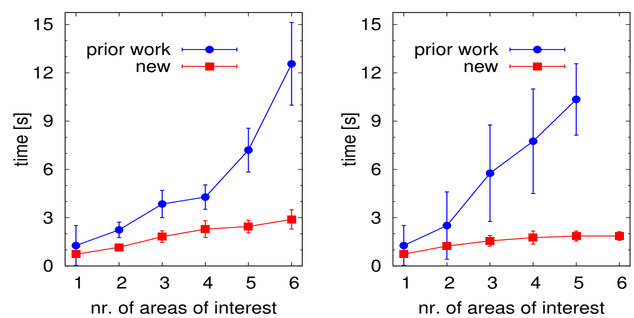


Fig. 2. An example of an environment used in one of the experiments. Areas of interest are displayed as red boxes with spherical obsticals obstructing the path of the AUV.



(a) task ϕ_1: "all" (b) task ϕ_2: "sequencing"

Fig. 3. Results when comparing the proposed approach (labeled as new) to prior work [6]. Bars indicate one standard deviation. A missing data point in the graph indicates the method timed out before obtaining a solution. Results include the time to construct the DFAs from the LTL formulas (in the order of milliseconds). For the proposed approach, results also include the time to construct the roadmap abstraction, which took between 0.1s–0.4s.

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