A Hybrid Planning Framework for Autonomous Underwater Vehicles

J.W. McMahon,1 B. Dzikowicz,1 B.H. Houston,1 and E. Plaku2
1Acoustics Division
2The Catholic University of America

Introduction: Autonomous underwater vehicles (AUVs) are a critical part of the Navy’s future in maintaining areas of undersea dominance such as intelligence, surveillance, and reconnaissance. A truly autonomous system should be able to execute an overarching mission composed of multiple tasks without human intervention. To accomplish this, the system must possess a planning framework that can reason about high-level tasks or goals and generate a plan of corresponding low-level actions that fulfills an overall mission. Current state-of-the-art AUV planning approaches require a human operator to input each low-level action, rather than prescribing the mission at a high level. This imposes a heavy burden upon the user when generating complex mission specifications. As such, there is a great need for the creation of intuitive mission planning interfaces and an autonomy framework to automatically handle the organization of both high- and low-level actions to accomplish the user-defined mission.

Here, we describe a new hybrid planning framework that generates plans accounting for high-level mission specifications as well as the underlying dynamics of the AUV and its environment. Using Linear Temporal Logic (LTL), a temporally structured language resembling English, tasks are described using propositions combined with logical (and, or, not) and temporal (next, eventually, always, until) connectives. For example, an inspection mission can be described as follows: “(always remain safe) and (eventually inspect areas A1, A2,...) and (if obstacle then avoid) and (if object of interest then explore surrounding area) and (if indication of moving object then track until identified).” The framework analyzes the mission description and derives from it the necessary underlying actions required to accomplish the overall mission.

Hybrid Planning Framework: Our new framework couples motion planning with a high-level reasoner, such as LTL model checking1,2 or goal-driven autonomy3 to account for complex missions, as shown in Fig. 1. In the present study, an LTL model checking algorithm is used to break down the general mission specification into a series of discrete tasks such as “inspect area A, inspect area B, inspect area C, etc.” This solution is then passed to a motion planner, which attempts to expand a tree of dynamically feasible and collision-free motions that accomplish the specified tasks. As the AUV attempts to implement the current task, feedback information is provided to the high-level reasoner, which in turn updates the discrete plan. The update process takes into account difficulties (such as the motion planner getting stuck in local minima), attempts to minimize the total path length, and flags failures (such as the motion planner exceeding an allotted amount of time). The process is repeated until a solution that accomplishes the entire mission is found.

Implementation and Experimental Results: The planning framework has been evaluated in numerical simulations and in preliminary field experiments. The left panel of Fig. 2 shows a representative solution trajectory superimposed on a simulated scene of an estuary. The right panel presents the mean runtime of the planning framework to generate solution trajectories as a function of mission complexity considering a variety of mission specifications, expressed using LTL. The mission types include sequencing, which imposes a strict order on the execution of tasks; coverage, where the planner seeks to minimize the overall trajectory length; partial ordering, where the first half of the regions are inspected in any order and then the second half in any order; and a zig-zag mission, where alternate regions from each half are inspected. These examples illustrate the expressiveness of LTL to construct complex missions.

A preliminary field experiment was conducted with an Iver2 AUV in the Chesapeake Bay area. The mission consisted of inspecting five regions of interest in succession while avoiding collisions with artificially imposed obstacles. The planner, in a matter of a few seconds, computed a collision-free and dynamically feasible trajectory that enabled the AUV to accomplish...
the mission. Agreement between the planned and actual trajectory (as shown in Fig. 3) demonstrates that the planner is capable of quickly generating feasible motions that can be followed by the vehicle to successfully accomplish a complex mission.

Conclusions and Future Work: We have demonstrated a new hybrid planning framework that successfully integrates both high-level reasoning and low-level motion planning. This planner is a powerful tool that can be used to quickly generate low-level actions that
accomplish high-level missions. Future work includes integration with goal-driven autonomy as a high-level reasoner and sensor data gathered during execution in order to autonomously adapt to changing environmental and contextual conditions. Further experiments are also being conducted to evaluate the effectiveness of the planner in mine countermeasures scenarios for reacquisition and identification.

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References

A Fresnel Zone Plate Lens for Underwater Acoustics

D.C. Calvo, A.L. Thangawng, M. Nicholas, and C.N. Layman
Acoustics Division

Introduction: Focusing sound in a liquid environment is important in applications such as undersea acoustical imaging and nondestructive evaluation using immersion scanning. These applications typically use high-frequency sound near the MHz regime. Operation at lower frequencies and with high resolution using conventional lenses or two-dimensional transducer arrays is challenging when there are size, weight, and complexity constraints associated with a large aperture. Furthermore, short focal lengths in conventional lens-based receiver systems can require lenses that are impractically thick.

Fresnel zone plates (FZPs) offer thin, diffraction-based alternatives to forming a focus and are commonly used in soft X-ray, microwave, and optical engineering. In the standard FZP, the focus is caused by constructive interference of diffracted sound through annular gaps in a “plate,” which otherwise blocks the transmission of sound. At the Naval Research Laboratory, we have developed an underwater acoustic FZP lens (Fig. 4) by using thin, acoustically opaque rubber foam rings bonded to an acoustically transparent thin rubber substrate.1,2 Owing to the thin and flexible construction, large apertures can be deployed from small volumes.

FZP Experimentation and Results: We characterized the prototype FZP in a laboratory test tank. A piston source insonified the lens with a tapered plane wave and a small omnidirectional hydrophone scanned the transmitted sound field. The directional source allowed control over the number of insonified zones depending on separation from the lens. The \( D = 33.2 \) cm diameter lens was designed to have an \( F = 8.75 \) cm primary focal distance when insonified by an ideal plane wave at 200 kHz (\( \lambda = 7.4 \) mm). This focal length is relatively short since a ray between the aperture edge and focus makes an angle of \( \theta = 62^\circ \) with the lens axis. For these conditions, and assuming ideal sound blocking, a focal gain of 24 dB was predicted. The actual focal distance and gain depends on the curvature of the incident acoustic wavefront, the number of zones insonified (both vary with source–FZP separation), and the effectiveness of the rubber foam at blocking sound. Figure 5 shows a comparison between measured and predicted focusing when half the zones are insonified within a –6 dB radius attained at 50 cm source separation. The measured focal gain, defined as the ratio of the square of the focal pressure to the square of the incident pressure on the front-face centerline, was 16.5 dB.

FIGURE 4
Fresnel zone plate (FZP) lens for underwater acoustic use. The FZP is shown both installed in a test frame (right) and coiled (left).