Dynamic Trajectory Planning for Autonomous Underwater Vehicle Docking

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Abstract — AUVs are increasingly being considered for localised persistent mission applications in support of military applications. Submerged docking stations can be used to facilitate localised persistence by providing battery recharge, data transfer, and even shelter. A docking guidance system based on the Pseudo-Spectral based optimal control theory is proposed to achieve reliable autonomous docking in the presence of cross currents and dynamic obstacles. Simulation results demonstrate that the guidance system can provide fast, efficient and tractable generation of near-optimal smooth trajectories for real-time docking.

1 Introduction

A major challenge in the use of Autonomous Underwater Vehicle (AUV) systems for intelligence, surveillance, and reconnaissance (ISR), antisubmarine warfare (ASW) and mine countermeasure (MCM) applications is their ability to remain on station for prolonged periods. The use of submerged docking stations (DS) with recharging and data transfer facilities has been explored in the literature as a means of extending AUV persistence well beyond the limitations of the AUV’s inherent battery and data storage constraints [1, 2]. Docking an AUV with a DS is a complex process requiring the AUV to guide itself towards and into a DS in an environment made all the more challenging by the presence of dynamic currents and moving obstacles.

The optimal guidance system proposed in this paper is based on the Pseudo-Spectral (PS) based guidance system [3, 4]. The capability of the PS method to generate near-optimal trajectories is demonstrated in many applications mostly in an offline context but with increasing computation and sufficiently simple problem definition, computation time can be reduced to a timeframe suitable for online applications. The PS guidance system explicitly incorporates the AUV’s dynamic and kinematic constraints including, thruster authority and rate of change constraints, as well as constraints associated with the docking station geometry and approach angle, together with the current disturbance vector field. The structure of the guidance system allows generation of 6 DoF trajectories from any arbitrary initial vehicle state, i.e., 6 DoF pose and velocities of the vehicle, assuming there is a valid solution. The system also satisfies the higher-order term vehicle dynamics such as acceleration, thus guaranteeing controllability and smooth arrival of the AUV into the DS during the terminal docking phase. Additionally, the PS guidance system can support efficient docking performance as measured by time taken, energy consumed, risk, or any arbitrary combination of docking performance objectives as required for the mission.

The purpose of this paper is to describe the development of a docking guidance system for AUV docking. The DS, currently under development at Flinders University, is a cylindrical tube with a conical entrance and is equipped with a GPS, an attitude and heading reference system (AHRS), an Acoustic Doppler Current Profiler (ADCP) and an Ultra-Short Baseline (USBL) beacon transponder. The DS is designed to be mounted below a buoyant platform providing passive stability. The AUV, a customised version of the Graal Tech X300 as shown in Fig. 1, measuring 3 m in length and 0.15 m in diameter, is similarly equipped with an AHRS, GPS, DVL and USBL array with acoustic modem capabilities. The AUV is also equipped with a high resolution forward looking multibeam sonar and a camera for imaging the DS. These instruments allow the AUV to determine the location of the DS and measure water current around the DS by allowing the DS to transmit its state, pose and velocities, to the AUV guidance system, via the USBL modem.

AUV motion in the surge direction is provided by a single bi-directional rear thruster that can provide a maximum thrust of 50 N. Two lateral and two vertical thrusters, each producing 20 N are used for the yaw, sway, pitch and heave control. This consequently leads to decoupling of the motions in the actuator systems used in the AUV. Roll is the only DoF that is not actuated but is passively stable due righting forces.

2 Results and Discussion

To demonstrate the effectiveness of the proposed guidance system, a simulator was built using a high-fidelity AUV simulation model implemented in the ROS default simulation environment Gazebo [5], as shown in Fig. 2. This includes a dynamic positioning PID controller, hydrodynamic and hydrostatic modelling as well as models of thruster dynamics, seabed and sea surface effects. In this simulation a hydrodynamic model of the form presented in [4] is implemented to provide a highly accurate model of the motion of an underwater. The Legendre-Gauss-Lobatto (LGL) PS optimisation utilised within this simulation is provided by the PSOPT library [6] encapsulated within a custom ROS wrapper for interfacing with the rest of the ROS framework.

In the simulated docking scenario, a strong cross-current disturbance was applied to the operating
environment. This current was randomly changed in a Brownian sense with an average magnitude of 0.5 m/s in a westerly direction. The guidance system on the AUV receives information from the DS regarding the DS pose and its surrounding current components. This information is transmitted by the USBL modem mounted on the DS. The location and size of obstacles as would be detected by a forward-looking sonar, were also provided. Using this data, the trajectory planner, utilising 20 collocation (evaluation) points, then generated an optimal trajectory, which was then executed by the dynamic positioning PID controller on-board the AUV, as shown in Fig. 2. The docking trial was repeated 10 times as shown in Fig. 3, to ensure reliability and repeatability of the generated trajectories.

The trials confirmed that a maximally smooth trajectory requiring minimal accelerations and meeting all terminal and collision conditions, can be generated. All the trajectories generated can be tracked by a minimally tuned PID controller with no knowledge of the vehicle’s dynamics. The simulations also revealed that the planner took an average of 0.90 s with $\sigma^2 = 0.27$ s to compute on hardware (i7-7600U) not dissimilar to that which would be available as a backseat driver on a target AUV platform.

3. Conclusion

A system for efficient AUV docking with a DS is presented in this paper. The paper demonstrates that an LGL-PS trajectory generator can generate a trajectory that minimises effort and control complexity while still meeting operational requirements such as collision avoidance, time, and energy criteria. The solution is suitable for real-time application and suitable for implementation on an AUV. Sea trials with the AUV and DS are underway to validate the guidance system.

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References


Figure 3. 3D trajectories performed by the AUV travelling around an obstacle over 10 trials, each trial is assigned a corresponding colour for the obstacle outline and the trajectory.

Biography

Karl Sammut is a Professor with the Engineering Discipline in the College of Science and Engineering at Flinders University, and is the Director of the Centre for Maritime Engineering and Theme Leader for the Maritime Autonomy Group.