Autonomous Underwater Docking and Recharging

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The development of autonomous underwater docking systems is essential due to the limited endurance of autonomous underwater vehicles (AUVs), which necessitates their frequent retrieval by surface vessels for recharging - a process that can be time-consuming and expensive. These docking systems, when coupled with marine energy devices like wave energy converters (WECs) or when configured to harness power from cabled oceanographic observatories, can extend the longevity of AUV missions and reduce the dependence on ship support through their autonomous capabilities. Consequently, this integration leads to a significant reduction in carbon footprint and operational costs. Not only does it benefit the environment by replacing fossil fuel-dependent vessels with renewable energy sources, but it also provides a promising solution for expanding our understanding of the ocean by enabling AUVs to engage in long-term deployments, such as bathymetric mapping, inspection of submerged structures, and monitoring ocean conditions in deep waters. However, achieving autonomous docking in challenging conditions, including strong ocean currents and wave forces, remains an active area of research. Therefore, we present a docking framework that incorporates flow state estimation into the design of a model predictive controller (MPC) for achieving autonomous underwater docking with a WEC in diverse ocean conditions. Furthermore, this framework adequately addresses the influence of wave forces on the AUV.

I. Docking Framework

By integrating flow state estimation with MPC, the AUV can dynamically adapt and make informed decisions to effectively counteract ocean flow influences during docking. Our previous study [1] demonstrated its efficacy under diverse flow conditions. Here, we extend upon the approach presented in [1] by integrating the influence of wave forces into the vehicle dynamics. For more detailed information, we refer the readers to [2].

The discretized vehicle motion model can be defined as

$$\mathbf{x}(k+1) = f(\mathbf{x}(k), \mathbf{u}(k)), \tag{1}$$

where $\mathbf{x} \in \mathbb{R}^{12}$ represents the vehicle state vector and $\mathbf{u} \in \mathbb{R}^6$ represents the vehicle control input.

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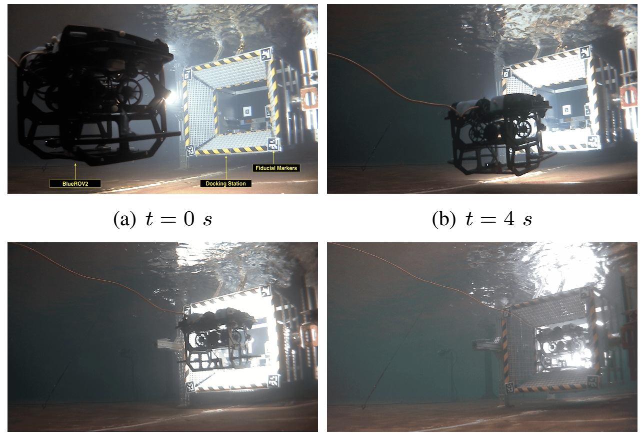

(a) $t = 0\ s$ (b) $t = 4\ s$ (c) $t = 8\ s$ (d) $t = 16\ s$

Fig. 1: Successful attempt to dock autonomously with an oscillating docking station under 0.1 m waves, using fiducial markers. The sequence of images illustrates the approach and docking phase of the vehicle.

At time $k = t$, the controller seeks to find a sequence of optimal control inputs $\mathbf{U}^\star = \{\mathbf{u}^\star(0), \cdots, \mathbf{u}^\star(N)\}$ by minimizing the objective function J such that

$$\mathbf{U}^\star = \underset{\{\mathbf{u}(0),\cdots,\mathbf{u}(N)\}}{\operatorname{argmin}} J = \sum_{k=\kappa}^{t+N-1} \Big[\|\mathbf{x}(k) - \mathbf{x}_W(k)\|_Q^2 + \|\mathbf{u}(k+1) - \mathbf{u}(k)\|_R^2 - \alpha\mathcal{F} \Big] + \|\mathbf{x}(N) - \mathbf{x}_W(N)\|_P^2 \tag{2}$$

$$\text{subject to (1)},\ \mathbf{x}(0) = \mathbf{x}_0,\ \mathbf{x}_{min} \leq \mathbf{x}(k) \leq \mathbf{x}_{max}, \quad \mathbf{u}_{min} \leq \mathbf{u}(k) \leq \mathbf{u}_{max},$$

where $\mathbf{x}_W \in \mathbb{R}^6$ represents the WEC state vector, N represents the prediction horizon, $\mathcal{F}$ represents the observability of the ocean flow state, α represents a scalarization factor, and P, Q, and R are weight matrices.

II. Results and Discussion

Simulation results demonstrate successful docking under various flow conditions. To validate the performance of the docking framework in the presence of waves, we conducted trials at the O.H. Hinsdale wave basin on a BlueROV2, achieving a 100% success rate in waves of 0.05 m and 0.1 m, and a 40% success rate in waves of 0.2 m. Furthermore, we achieved an 80% success rate for autonomous docking with an oscillating docking station under waves of 0.1 m (Fig. 1).

References

[1] R. Vivekanandan, D. Chang, and G. A. Hollinger, "Autonomous underwater docking using flow state estimation and model predictive control," in *Proc. IEEE International Conf. on Robotics and Automation*, pp. 1062–1068, 2023.

[2] T. I. Fossen, *Handbook of marine craft hydrodynamics and motion control*. John Wiley & Sons, 2011.