Model Predictive Control for Underwater Vehicle Rendezvous and Docking with a Wave Energy Converter

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***Abstract*— Applications of underwater research using marine vehicles are currently limited due to restrictions on energy and data-storage resources available on the vehicles. To increase the endurance of the vehicles, the problem of vehicle docking for recharging and data transmission has recently gained increasing attention. In this paper, we study vehicle docking with a wave energy converter (WEC) using model predictive control (MPC). To overcome restrictions of existing algorithms in the presence of ocean currents, we design our MPC with a vehicle model that accounts for the influence of ocean current disturbances. To demonstrate the robustness and effectiveness of our approach, we simulate vehicle docking with a WEC whose motion is limited to only vertical oscillations under various ocean conditions. In the future, we intend to incorporate a higher fidelity motion model of the WEC and test the performance of our approach under complex environmental conditions.**

I. Introduction

Marine vehicles, such as autonomous underwater vehicles (AUVs) or remotely-operated vehicles (ROVs), traditionally rely on research vessels for deployment and retrieval. Limited energy resources of AUVs and tethered connectivity of ROVs constrain survey lengths and subsequently increases the operational costs significantly. Underwater docking stations that can recharge vehicles and transmit their data offer a potential solution to extend the endurance of vehicles. Motion planning for underwater docking is a difficult and unsolved problem. In this paper, we study the docking of a marine vehicle with a wave energy converter (WEC) using model predictive control (MPC) under various ocean conditions. To counter the environmental forces acting on the vehicle, we design an MPC using a vehicle motion model that accounts for ocean current disturbances represented by flow velocity. For simplicity, the WEC's motion is limited to vertical sinusoidal oscillations. Then, we evaluate the robustness and effectiveness of the docking strategy. Future work includes incorporating higher fidelity WEC motion and complex ocean waves into our docking approach.

II. Related Works

In particularly relevant prior work, [1] introduced a real-time controller for ROVs based on MPC to follow a desired trajectory in a water column. The MPC is designed to account for the water current estimates from the localisation filter. Similarly, [2] used MPC for the station keeping of an ROV in ocean waves. The state estimator designed employs linear wave theory to forecast and adjust the vehicle's state for the wave action. In [3], a finite hoizon MPC was developed to verify the concept of docking to an offshore WEC with simplified motion along the vertical axis. But, their algorithm works only in the absence of ocean current disturbances. Our work complements [3] by seeking a more comprehensive numerical framework further connecting the environmental disturbances experienced by the vehicle.

III. Method

With the goal of reaching the dock point from an arbitrary location, the vehicle must be able to navigate autonomously through unexplored obstacle-free environments considering nonlinear and differential constraints. Based on the work done in [3], a closed-loop MPC docking strategy is developed with the modification to account for ocean current disturbances. The objective of this controller is to perform precise docking by predicting the desired control input of the vehicle.

In this paper, we use a six-degrees-of-freedom vehicle motion model to design vehicle control in the presence of ocean currents. The model uses two reference frames: Inertial frame (earth-fixed) $\{n\}$, coincidental with the North-East-Down (NED) coordinate system, and the body-fixed frame $\{b\}$. Vehicle motion is described in terms of vehicle pose $\eta \in \mathbb{R}^6$ in $\{n\}$ and vehicle linear and angular velocity $\nu \in \mathbb{R}^6$ in $\{b\}$. Then, vehicle motion can be described by

$$\dot{\eta} = J(\Theta)\nu \tag{1}$$

$$M_{RB}\dot{\nu} + M_A\dot{\nu}_r + C_{RB}(\nu)\nu + C_A(\nu_r)\nu_r + D(\nu_r)\nu_r + g(\eta) = \tau, \tag{2}$$

where $\nu_r = \nu - \nu_c \in \mathbb{R}^6$ represents the vehicle velocity relative to ocean current velocity $\nu_c \in \mathbb{R}^6$; $J(\Theta)$ is a transformation matrix from $\{b\}$ to $\{n\}$ with respect to vehicle orientation Θ; M_{RB} and M_A are the rigid body and added masses; C_{RB} and C_A are Coriolis and centripetal terms due to the rigid body and added masses, respectively; D and $g(\eta)$ represent the hydrodynamic damping and the hydrostatic restoring forces, respectively; and $\tau \in \mathbb{R}^6$ represents the forces and moments acting on the vehicle.

Eqs. (1) and (2) represent the vehicle kinematics and dynamics models, respectively. For brevity, we refer the readers to [4] for details about the model. Let us define vehicle state vector $\mathbf{x} = [\eta^T, \nu^T]^T \in \mathbb{R}^{12}$ and control input $\mathbf{u} \in \mathbb{R}^6$ that satisfies $\tau = B\mathbf{u}$, where B is the thruster allocation matrix. For simplicity, we assume constant

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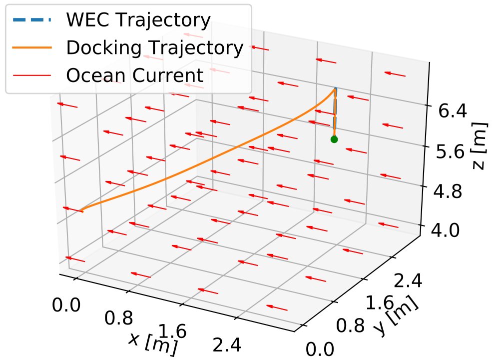

Fig. 1. Example vehicle docking trajectory under ocean current disturbances. The vehicle successfully approaches the WEC and moves with it.

irrotational flow velocity (i.e., $\dot{\nu}_c = 0$) in this paper. With this assumption, a discretized vehicle motion model is given by

$$\mathbf{x}(k+1) = f(\mathbf{x}(k), \mathbf{u}(k)), \tag{3}$$

where f represents the discretized vehicle motion derived from (1) and (2).

To analyse the feasibility of the proposed strategy for docking, the simulated WEC is limited to only translatory heave motion with sinusoidal oscillations. Let us define WEC state vector $\mathbf{x}_W \in \mathbb{R}^6$ whose vertical motion is described by

$$\dot{z}_W = \omega A cos(\omega t), \tag{4}$$

where ω and A are the frequency and amplitude of oscillation, respectively.

A sequence of the optimal control input $\mathbf{U}^\star = \{\mathbf{u}^\star(0), \cdots, \mathbf{u}^\star(N)\}$ is obtained by minimizing the objective function J such that

$$\mathbf{U}^\star = \underset{\{\mathbf{u}(0),\cdots,\mathbf{u}(N)\}}{\text{argmin}} \quad J = \sum_{k=0}^{N-1} \Big[\parallel \mathbf{x}(k) - \mathbf{x}_W(k) \parallel_Q^2 + \parallel \mathbf{u}(k+1) - \mathbf{u}(k) \parallel_R^2 \Big] + \parallel \mathbf{x}(N) - \mathbf{x}_W(N) \parallel_P^2 \tag{5}$$

$$\text{subject to } (3),\ (4),\ \mathbf{x}(0) = \mathbf{x}_0,\ \mathbf{x}_{min} \le \mathbf{x}(k) \le \mathbf{x}_{max}, \quad \mathbf{u}_{min} \le \mathbf{u}(k) \le \mathbf{u}_{max},$$

where N is the prediction horizon, and P, Q, and R are weight matrices.

IV. Results

In our implementation, only the first action in the resulting sequence of optimal control is executed, and this process is repeated until a vehicle and a WEC meet closely together. For the discretized vehicle motion model in (3), we have a time step $dt = 0.1\ s$. We empirically chose the prediction horizon window $N = 10$ and a convergence tolerance for docking with a precision of 0.005 m. For simulations, the initial heading of the vehicle is set to 0 °, and the vehicle navigates from a starting position at $(x, y, z) = (0, 0, 5)$ until it meets the WEC oscillating at $(x_W, y_W) = (2, 3)$ in the z axis with the target heading of 90 °.

Fig. 1 illustrates a trajectory followed by the vehicle to perform docking under the influence of a constant ocean current moving with a speed and heading of 0.5 m/s and 180 °, respectively. The vehicle first moves to the top position of the vertical trajectory of the WEC because the vehicle approaches the WEC closely. However, since the WEC is constantly moving, the vehicle follows the WEC and achieves docking to the WEC at the bottom position of the trajectory where the convergence tolerance for docking is satisfied.

The performance of the controller is tested under different conditions of ocean current disturbances as shown in Table I. Note that the vehicle model in (3) accounts for the influence of ocean currents on the vehicle motion. In this paper, we assume the perfect knowledge of ocean currents, and this knowledge is incorporated into the MPC design in (5). Despite different ocean conditions, the path lengths achieved by vehicles are similar. We also evaluate cumulative cost which is a sum of the optimal values of J in (5) associated with optimal control inputs $\mathbf{U}^\star$ for the entire time period, shown in the last column of Table I. It can be noted that the cumulative cost is lower when the heading of the ocean current is along the direction of the WEC. This demonstrates that the vehicle consumes more energy to counter the effect of an opposing ocean current.

TABLE I
PERFORMANCE ANALYSIS OF THE PROPOSED STRATEGY

Ocean Current Speed $[m/s]$	Ocean Current Heading [°]	Path Length $[m]$	Cumulative Cost
0	-	4.92	2650.87
0.5	0	4.95	2507.11
	90	4.92	2667.41
	180	4.96	2787.98
1	0	5.02	2291.5
	90	4.96	2580.07
	180	5.03	2942.46

V. Conclusions and Future Work

In this work, we have designed an MPC based strategy to demonstrate the robustness of docking under various ocean conditions. We have shown that our MPC can guide an AUV for reliable docking in the presence of ocean current disturbances. Future work includes incorporating a higher fidelity WEC motion and complex environmental conditions, such as time-varying ocean currents with depth-dependent wave-current interactions, into our docking approach. Furthermore, we intend to compare our approach with baseline approaches such as a PID controller and a linear quadratic regulator. We also plan to conduct field trials by deploying the proposed approach on a real robot.

References

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