

# Manipulator-Effort-Aware MPC for Body Motion Coordination of an Underwater Walking Robot under Ocean Current Disturbances

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## I. INTRODUCTION

In moored mine clearance tasks, an underwater walking robot is required to maintain body stability while reliably grasping a target rope using a manipulator. In practice, however, this task is challenging because the robot is continuously exposed to ocean-current disturbances, and the manipulator may experience increased effort during grasping. Conventional approaches treat body motion and manipulator operation independently, which makes it difficult to adapt the body motion according to the manipulator burden during the task. To address this limitation, this paper proposes a manipulator-effort-aware MPC framework for body motion coordination of an underwater walking robot [1]. The proposed method employs the norm of manipulator joint torques as a measure of task effort and incorporates it into the prediction model and cost function, allowing the controller to adjust body approach motion and posture compensation when manipulator effort increases. As a result, the proposed framework improves body stability while reducing manipulator burden under ocean-current disturbances.

## II. MPC-BASED WBC FRAMEWORK

The proposed framework formulates underwater robot manipulation as an MPC problem that adjusts body approach motion and posture according to manipulation effort. This enables coordinated control beyond the previous decoupled multi-legged and dual-manipulator architecture [2].

$$\min_{\mathbf{u}} J = \sum_{k=0}^{N-1} \left( \|\mathbf{x}_k - \mathbf{x}_k^{ref}\|_{\mathbf{Q}}^2 + \|\mathbf{u}_k\|_{\mathbf{R}}^2 + \|\Delta\mathbf{u}_k\|_{\mathbf{R}_\Delta}^2 + \phi_{\text{man}}(d_k) \right) \quad (1)$$

$$\text{s.t. } \mathbf{x}_{k+1} = f(\mathbf{x}_k, \mathbf{u}_k, d_k),$$

$$\mathbf{u}_{\min} \leq \mathbf{u}_k \leq \mathbf{u}_{\max},$$

$$g(\mathbf{x}_k, \mathbf{u}_k) \leq 0,$$

$$\mathbf{u}_k = \begin{bmatrix} \Delta x_{ref,k} \\ \Delta p_{ref,k} \end{bmatrix}, \quad d_k = \|\boldsymbol{\tau}_{arm,k}\|. \quad (2)$$

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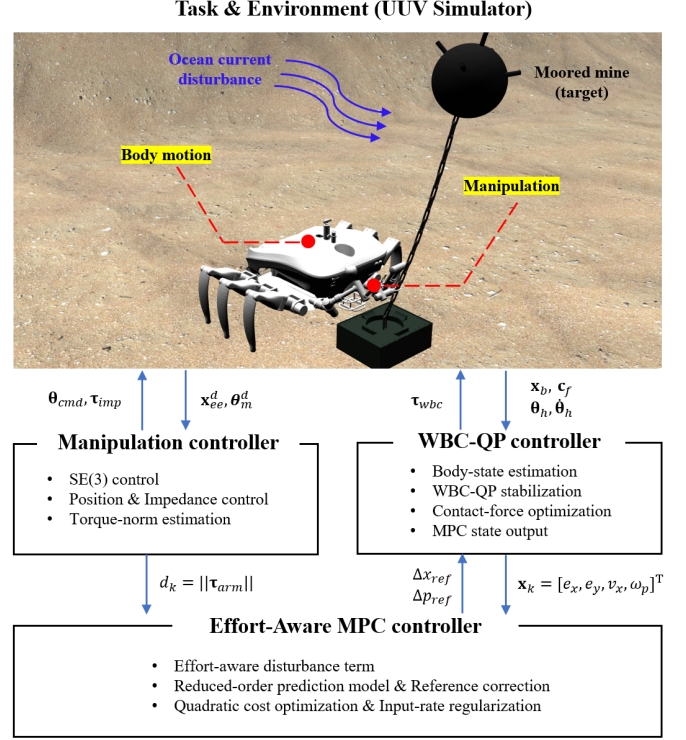


Fig. 1. Overall control architecture of the proposed manipulator-effort-aware MPC framework

Here,  $\|\mathbf{e}_k\|_{\mathbf{Q}}^2$  denotes the weighted state tracking error,  $\|\mathbf{u}_k\|_{\mathbf{R}}^2$  is the control effort penalty,  $\|\Delta\mathbf{u}_k\|_{\mathbf{R}_\Delta}^2$  penalizes rapid input variation, and  $\phi_{\text{man}}(\mathbf{x}_k, d_k)$  represents the manipulator-effort-related penalty term.  $\mathbf{x}_k$ ,  $\mathbf{u}_k$ , and  $d_k$  denote the system state, control input, and effort-related term, respectively. The equality constraint represents the system dynamics, while the inequality constraints enforce the input bounds and additional state/input limitations.

Fig. 1 illustrates the overall control architecture of the proposed manipulator-effort-aware MPC framework. The dual-arm manipulation controller generates manipulation commands and the effort-related term  $d_k$ , while the WBC-QP controller provides the reduced body-motion state  $\mathbf{x}_k$ ; these signals are then used by the effort-aware MPC layer to compute the body reference corrections  $\Delta x_{ref}$  and  $\Delta p_{ref}$  for coordinated underwater loco-manipulation.

Here,  $\mathbf{x}_{ee}^d$  and  $\boldsymbol{\theta}_m^d$  denote the desired end-effector pose and desired manipulator motion, respectively, while  $\mathbf{x}_b$ ,  $\mathbf{c}_f$ , and  $\boldsymbol{\theta}_h$  represent the body state, foot contact state, and legged joint state. The term  $d_k$  denotes the manipulator-effort-

related input derived from the torque norm, and  $\mathbf{x}_k$  denotes the reduced state used for MPC prediction. The MPC outputs  $\Delta x_{ref}$  and  $\Delta p_{ref}$  correspond to the corrective references for body approach motion and pitch motion, respectively.

### III. EXPERIMENT

The experiments were conducted in a ROS1 noetic–Gazebo environment using the DAVE Project based on the UUV-Simulator. A six-legged underwater walking robot and a moored-mine model were implemented in the simulation, and the robot grasped the mooring rope during the experiments. The right arm was controlled by impedance control to maintain a desired workspace, the robot body was stabilized by a WBC-QP controller, and the proposed manipulator-effort-aware MPC was applied as a supervisory layer to adjust the body approach motion and posture.

A unidirectional ocean current was applied from the rear to the front of the robot, and the current speed was increased from 0.5 knot to 2.5 knot in 0.5 knot increments. The baseline case without MPC and the proposed case with MPC were compared under the same rope-grasping condition. The main evaluation metric is the norm of the manipulator torque, while the forward body displacement and body pitch variation are additionally monitored to verify the induced body-motion coordination under current disturbances.

When the robot interacted with the moored mine using only decoupled individual controllers without the proposed MPC, the manipulator joint torques continuously increased as the ocean-current disturbance grew. In particular, the torques of Joint 1 and Joint 5 showed a tendency to exceed the torque saturation limit, indicating the possibility of unstable or unsafe operation. This behavior became evident when the current speed exceeded approximately 2.0 knots.

In contrast, when the proposed integrated body–manipulator control with the effort-aware MPC was applied, the robot adaptively adjusted its body posture and motion so as to prevent excessive growth of manipulator torques. As a result, the joint torques remained below the saturation limit, and the robot exhibited mechanically more stable behavior against external disturbances.

These results demonstrate that the proposed effort-aware MPC controller can effectively integrate body and manipulator control by explicitly considering their interaction. Consequently, the framework improves disturbance response capability while reducing manipulator burden during moored-mine interaction tasks.

### IV. CONCLUSION

This paper presented an effort-aware MPC framework for coordinated control of a multi-legged underwater walking robot and a manipulator in moored mine clearance tasks. To avoid directly solving the full high-DOF whole-body dynamics, the proposed method separates body control and manipulator control, while introducing an upper-layer MPC to coordinate both subsystems. By using the norm of manipulator joint torques as an effort-related input, the controller

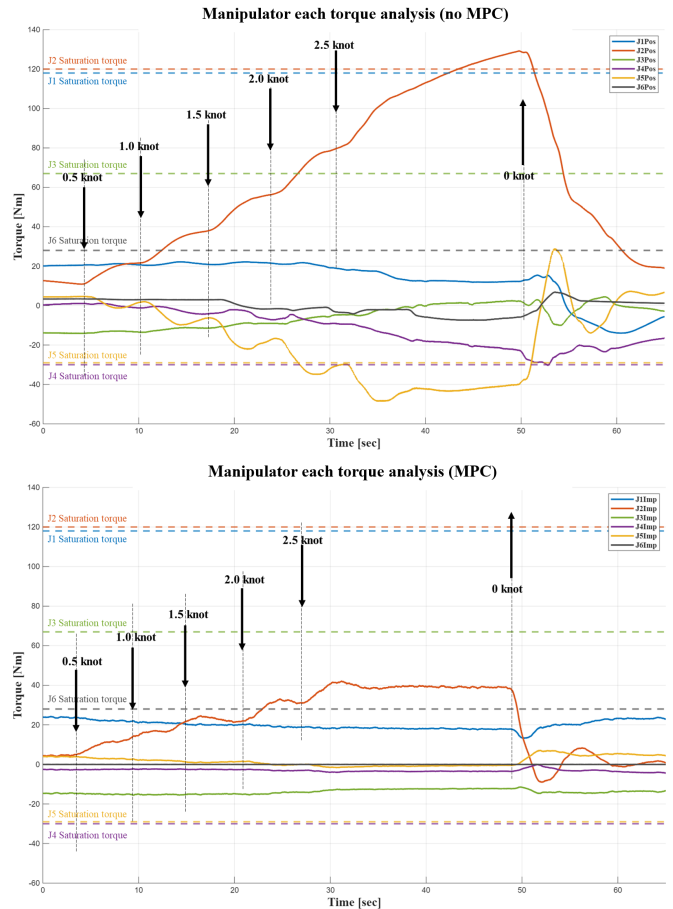


Fig. 2. Comparison of manipulator joint torques under ocean-current disturbances: top, without MPC; bottom, with the proposed effort-aware MPC.

adaptively modifies body motion and posture to reduce manipulator burden during rope-grasping interaction under ocean-current disturbances.

Simulation results in the UUV Simulator showed that, without the proposed MPC, manipulator torques continuously increased with stronger current disturbances and could exceed the torque saturation limit. In contrast, the proposed method maintained joint torques within the allowable range by generating adaptive body-motion compensation, resulting in more stable and mechanically safer behavior. These results demonstrate that the proposed framework can effectively integrate body and manipulator control and improve disturbance-response capability in underwater loco-manipulation tasks.

### REFERENCES

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