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A Controller Topology for Maneuvering a Floating Object via Direct Pushing with a Ship

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ABSTRACT

This paper presents a controller topology for maneuvering a floating object via direct pushing with a ship. The approach focuses on two primary tasks: the approach phase, where the ship aligns with and closes the distance to the object, and the manipulation phase, where the object is controlled while maintaining physical contact. The proposed control system combines trajectory planning with maneuvering the object by pushing at a strategically chosen point of contact, maintaining stability as it is guided toward the goal position. The controller is designed to handle the complex dynamics of ship-ice interactions and to mitigate external disturbances, including wind, waves, and currents.

The control system is implemented and evaluated through both simulation and experimental studies. Simulations are used to assess the robustness of the controller topology and its ability to perform effectively across a range of geometric configurations. Experimental results investigate the behavior of the control framework in model test scenarios, offering insights into practical considerations such as contact force variability and complex hydrodynamics not modeled in simulation.

Although this work focuses on single-agent manipulation of a floating object, it paves the way for future extensions to more complex scenarios. Future research will explore the use of multiple ships working cooperatively as a swarm to manipulate multiple floating objects, with an emphasis on minimizing interaction effects and ensuring effective coordination. These advancements aim to address broader challenges in Arctic ice management and other maritime applications involving collaborative systems for floating object control.

KEY WORDS

Pushing; Controller; Navigation; Ice; Port Operations

INTRODUCTION

The ability to manipulate floating objects using direct physical interaction is a promising capability in various maritime applications, ranging from Arctic ice management to port and harbor operations. Traditional methods for maneuvering such objects often rely on towing, dynamic positioning, or indirect hydrodynamic forces, each of which has inherent limitations in logistics, unstructured environments, and dynamically evolving conditions. A promising alternative is direct pushing, where a vessel maintains continuous or near-continuous contact with an object to guide it toward a desired position or orientation. This approach introduces unique control challenges due to the coupled dynamics of the ship-object system, external disturbances such as wind and waves, and the need for stable and predictable manipulation strategies.

This paper proposes a novel controller topology for maneuvering floating objects via direct pushing. Using a typical ship hull to push an object is considered non-prehensile manipulation, since there is no mechanism to grasp the floating object. Therefore, the point of application of force is critical to successfully manipulating the floating objects trajectory. The control strategy consists of two phases: the alignment, or approach, where the ship is aligned with the object to maximize range of control action, and the manipulation phase wherein the object is maneuvered while maintaining controlled contact. The controller integrates trajectory planning with a relative coordinate frame for manipulation, ensuring that the object is pushed at a strategically chosen point to maintain stability and minimize undesired rotational effects.

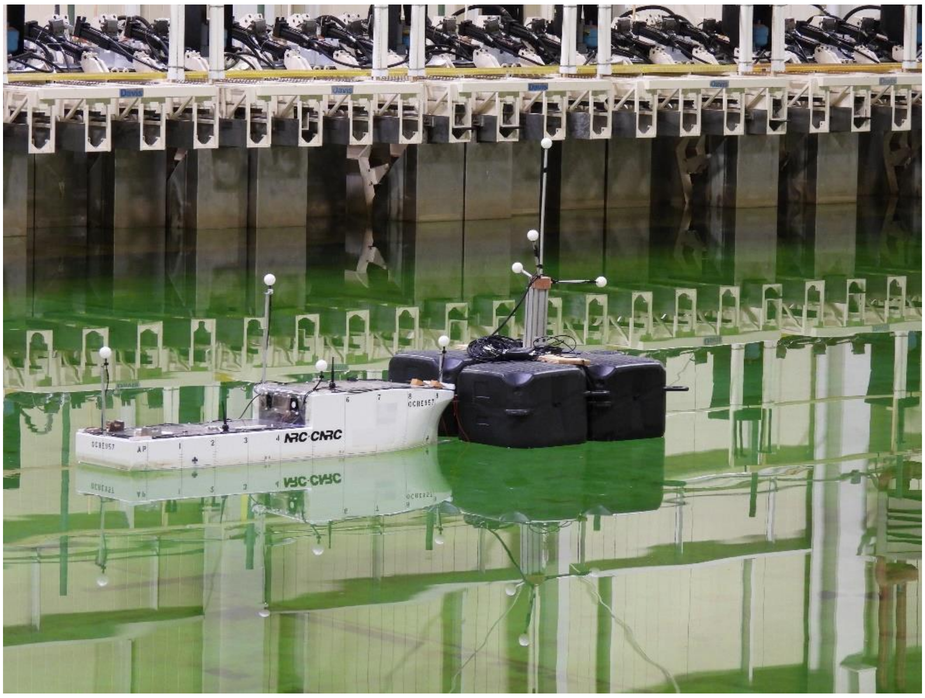

Figure 1. Photo of the 1:45 scale model supply vessel and floating target used during tank experiments at the NRC Offshore Engineering Basin in St. John’s, NL.

One of the key applications of this method is leveraging a single, conventional hull shape to effectively manipulate floating objects by pushing at the bow. The task of pushing a floating object along a desired trajectory in this manner is difficult for a manual pilot to achieve, as we experienced first-hand while conducting the experiments. By employing automatic control, the system can dynamically adjust pushing forces and contact angles, improving efficiency and reducing the reliance on human intervention. Therefore, this approach not only simplifies operational logistics but also enhances the adaptability of conventional vessels in constrained maritime environments. This enables the vessel to perform otherwise complex port operations, such as repositioning barges, guiding free-floating cargo, or clearing navigational paths, without requiring specialized tugboat designs or complex attachment mechanisms.

Beyond single-agent manipulation, this work lays the foundation for future extensions involving cooperative manipulation by multiple vessels. Such extensions could enable more efficient and flexible strategies for large-scale ice management, debris clearance, or other maritime applications where coordinated pushing is necessary. By addressing the fundamental challenges of direct-contact object manipulation, this research contributes to the broader field of autonomous maritime systems and paves the way for more advanced cooperative control frameworks.

BACKGROUND

Pushing is a type of manipulation widely used by autonomous robots to reshape their environments, especially when objects that are too large or heavy to be grasped and lifted should be positioned and oriented in the plane (Lynch and Mason, 1996; Stüber, *et al.*, 2020). Common tasks accomplished by robot pushing include clustering (Maris and Boeckhorst, 1996; Gauci, *et al.*, 2014), construction (Steward and Russell, 2006; Vardy, 2018; Petersen, *et al.*, 2019), and sorting (Pfeiffer, *et al.*, 1998; Melhuish, *et al.*, 2006; Vardy, 2012; Vardy, *et al.*, 2014). Lynch and Mason (1996) showed that any polygonal object has an edge through which it can be controllably pushed via stable pushes, assuming non-zero friction. A stable push is defined as a pushing interaction which does not break the contact between robot and object. Moreover, they provided a sufficient condition for switching edges. Lynch (1999) also derived a necessary and sufficient condition for small-time local controllability.

Interestingly, pushing floating objects with uncrewed surface vessels (USVs) as recently reviewed by Du *et al*. (2023) has only received little attention in the past. Most of the existing work has focused on using multiple vessels to push a single large floating object.

Many published control strategies assume that the autonomous vessels have already successfully approached the object to be pushed. Smith and coworkers described a system of autonomous tugboats that were in fixed contact with a barge and essentially operated as fixed thrusters. They introduced a tracking controller based on a set of adaptive control laws to move the barge along a desired trajectory (Esposito, *et al.*, 2008; Feemster and Esposito, 2011). In a similar setting, Bui and Kim (2011) describe a sliding mode controller for ship berthing. Choi (2020) also considered autonomous tugboats in constant contact with a larger ship to be pushed. However, the heading of the tugboats could change such that they operated as azimuthal thrusters instead of fixed thrusters. In their work, a traditional control strategy was proposed to achieve path following using different configurations of tugboats. Du *et al.* (2021a) considered the constant contact between autonomous tugboats and an unactuated ship to be established by rigid towlines. They proposed a multi-layer control scheme with a centralized high-level controller and local low-level control for each individual tugboat. They further showed the applicability of their controller topology under environmental disturbances (Du, *et al.*, 2021b).

Only few publications consider both the approaching and the pushing phase. Using traditional controls, Sartoretti *et al.* (2016) attained the approaching and pushing of a floating object with larger footprint by multiple smaller USVs, where the weight of each USV was equal to the object. The success of their approach relied on separating the controller for the approaching and pushing phase and using a centralized synchronization of the actions of each single USV. A similar approach was taken by Nesi *et al.* (2019), who compared three strategies for pushing an unmaneuverable boat. Between the strategies to control each USV individually, having the USVs stay in formation while pushing or synchronize the pushing efforts, they found the latter to yield the highest success probability for pushing along a straight line trajectory.

The only work known to the authors using a single USV to push a floating object was published by Rossario *et al.* (2020). They did not study the approaching phase but considered a circular disc in contact with the bow of an USV. Using a sliding mode controller they kept the disc stable at the bow while pushing it along a curved trajectory.

METHODOLOGY

The proposed control system relies on the relative position and orientation of the floating object with the ship under control. In this study, a symmetrical floating object with a square shape is considered, which simplifies the region for effective pushing to one side of the square. A general object would require some consideration of the uniformity, concavity, and ship orientation with respect to the inertial axes of the object to maximize control effectiveness. The ship in this study is also capable of pure sway motions utilizing bow and stern tunnel thrusters which allows for movement of the point of force application from side to side with minimal breaking of contact.

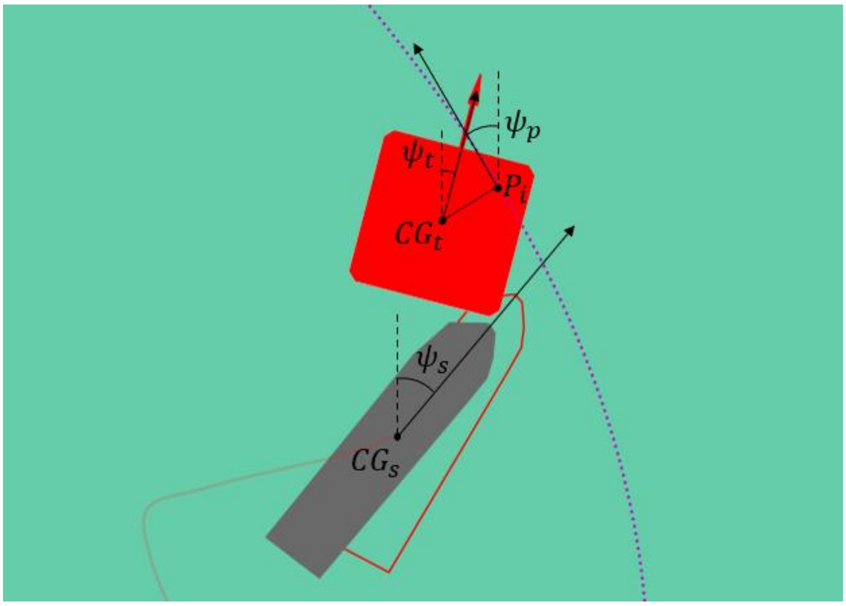

Figure 2. Geometry diagram showing angle definitions and coordinate frames for the considered obstacle pushing scenario.

As illustrated in Figure 2, the ship maintains a contact point at the bow relative to the body of the obstacle, which results in a force application offset from the center of gravity (C.G.) of the floating object. This offset generates a moment arm that produces a rotational effect on the object, allowing it to be steered in a controlled manner. By adjusting the heading, location, and contact force of the vessel, the system can effectively influence the trajectory of the manipulated object, ensuring that it follows the desired path. The desired point of contact between the bow of the vessel and the floating object, relative to the C.G. of the object (also called target) is given by

$$\boldsymbol{p}_{goal} = \boldsymbol{CG}_t + \boldsymbol{R}(\psi_t) \cdot (\boldsymbol{r}_t^{bow} + \left[0, K_{offset}\left(\psi_{t_{sp}} - \psi_t\right)\right])$$

Where $\boldsymbol{R}(\psi_t)$ is the 2-dimensional rotation matrix between the global frame and the target frame, $\boldsymbol{r}_t^{bow}$ is a fixed offset describing the desired point of contact relative to the target C.G. for neutral pushing, and K_{offset} is a gain on the heading error of the desired target heading (for trajectory tracking) and the actual target heading. The square brackets indicate x and y vector components, respectively. The relative angle between the vessel and the target heading is clamped to ±15 degrees or less for control calculations. This constitutes a proportional control action within the continuous range between the limits.

The control strategy integrates a trajectory planner for the pushed obstacle, from which a controller continuously adapts the vessel's heading and pushing force based on the relative position and orientation of the object. Figure 3 shows a block diagram of the overall control architecture. A dynamic positioning (DP) feedback control strategy is implemented to regulate the ship's heading and position, allowing it to seek a relative position to manipulate the target obstacle. The feedback system uses a state observer design to estimate the real time velocities in surge and sway and provide damping to the ship motion under control.

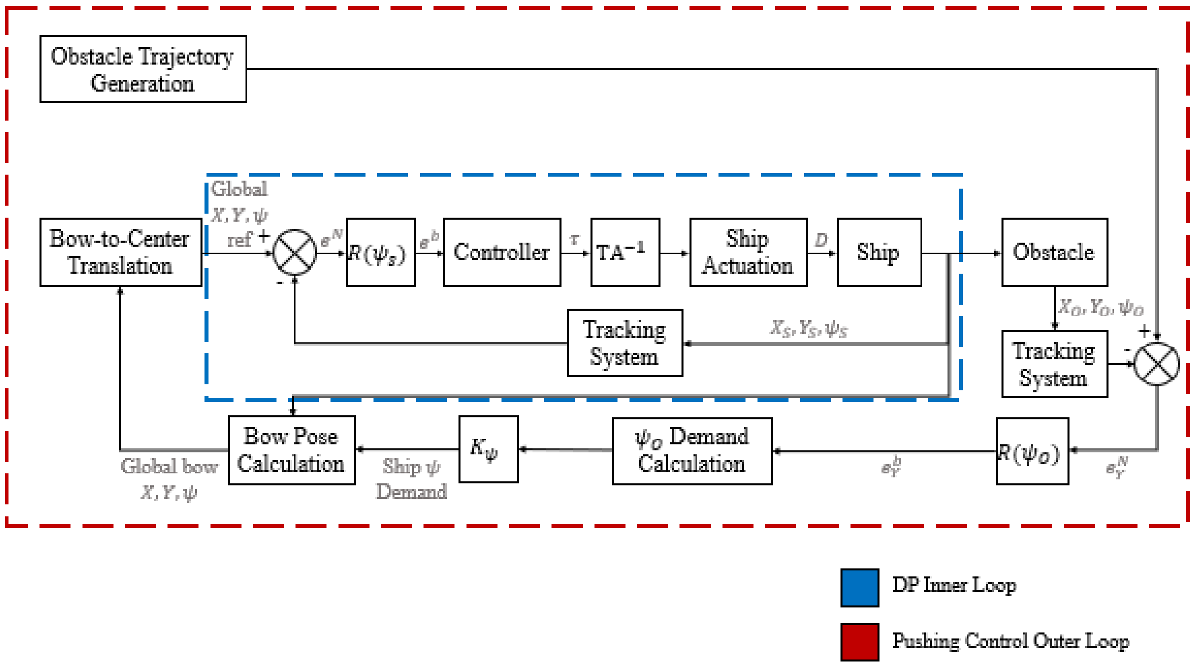

Figure 3. Block diagram showing angle definitions for generic obstacle pushing scenario.

To evaluate the effectiveness of the proposed method, the control approach is validated through both numerical simulations and experimental studies. Simulations are used to analyze the response of the system to assess trajectory-following performance. Experimental trials using scaled model tests provide further insights into real-world considerations, such as variable contact forces and unmodeled hydrodynamic effects.

SIMULATION RESULTS

To assess the performance and robustness of the proposed control system, numerical simulations are conducted using a physics-based floating object model. The simulation framework incorporates the same control architecture as the experimental setup in the offshore engineering basin. This allows for a direct comparison between simulated and real-world performance, helping to refine controller parameters and validate key assumptions before or during conducting physical experiments. Figure 4 shows a screenshot of the control interface using the physics simulation backend. Details of this control framework can be found in Murrant *et al.* (2021).

The simulation includes a dynamic model of the floating object, accounting for its mass, hydrodynamic forces, and rotational inertia using a physics library as described in de Schaetzen *et al.* (2024). The forces exerted by the ship at the contact point generate both translational and rotational motion, to model the moment arm effect observed in physical tests. Environmental disturbances are not introduced in the simulation at this time.

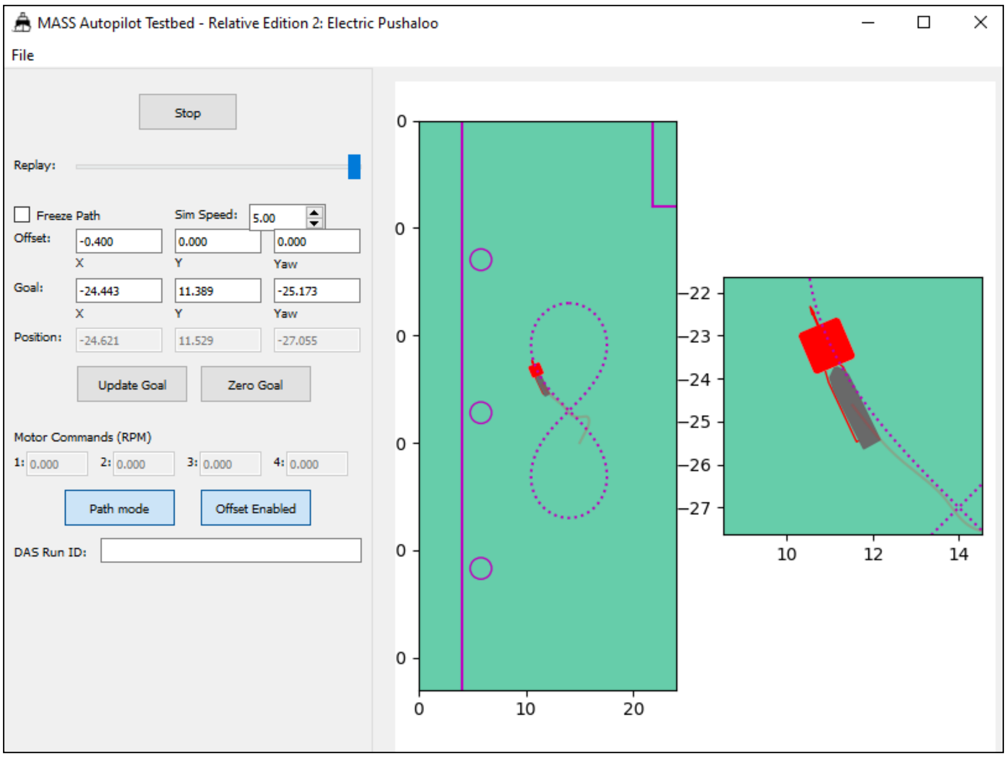

Figure 4. Screenshot showing control interface with physics simulation backend for controller development.

The control system operates in a separate thread within the simulation, using sensor-based feedback to adjust the ship's heading and pushing force according to the relative-DP approach. The trajectory planner ensures that the object is guided toward its target position while minimizing deviation due to path disturbances. The relative pushing offset controller dynamically adjusts the vessel's alignment, preventing loss of contact and maintaining stable control over the object.

A figure eight trajectory was tested due to the relative complexity of the trajectory for the obstacle to track, and to cover all possible cases of heading. The figure eight tracking was successful, however to remain consistent with the experimental results, Figure 5 shows the simulation results in terms of obstacle position and heading versus the ship setpoint for the straight path pushing scenario. These results show stable tracking of the obstacle along the path, which matches the performance of tracking achieved in the basin experiments.

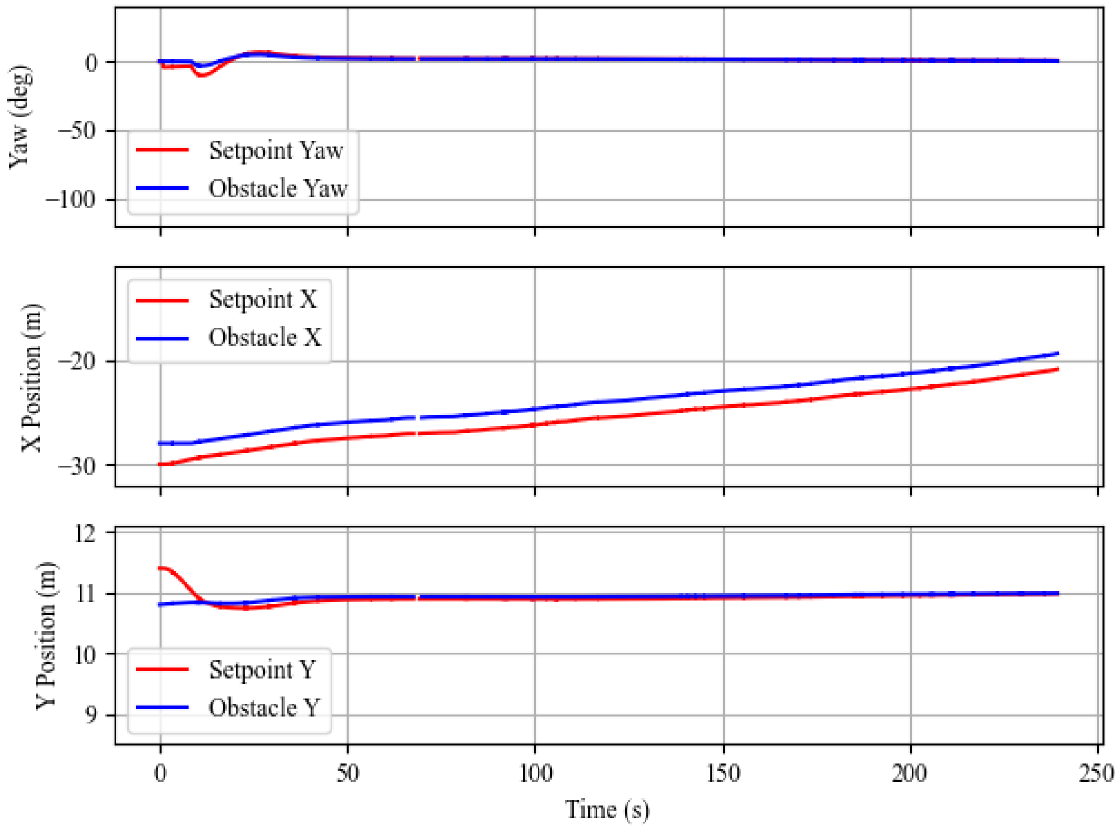

Figure 5. Time series plot of Setpoint (ship desired position) and Obstacle positions and orientations during straight pushing scenario in simulation.

In simulation, offsets were introduced to both the obstacle and ship under a variety of scenarios while attempting to track the figure eight trajectory. The controller in simulated experiments achieved trajectory following in most cases of initial conditions. This is an encouraging result for the relative offset approach to pushing a floating obstacle.

EXPERIMENTAL RESULTS

Experimental validation of the proposed pushing controller was conducted in the Offshore Engineering Basin using a 1:45 scale model of an offshore supply vessel. The target object was a 1m x 1m floating platform, representing a simplified version of a floating obstacle or ice floe. The position feedback is gathered from a visual motion capture system for both the ship and obstacle.

Figure 6 shows the target obstacle is able to track a straight path along the 11-metre Y-position in the basin. The target obstacle heading can be controlled within a tight band by the ship using this approach, within 2-3 degrees. This is encouraging for future work on pushing trajectories. The figure eight trajectory was not feasible in the current basin configuration, due to limitations in viable trackable area within the basin by the motion capture system.

It is worth noting that manipulating the floating object in this manner under manual control resulted in less accurate trajectory following than the automatic controller, even for experienced pilots with many previous hours of operation of this model. This is a promising application of automatic control that could have real world implications for how port operations are undertaken in the future.

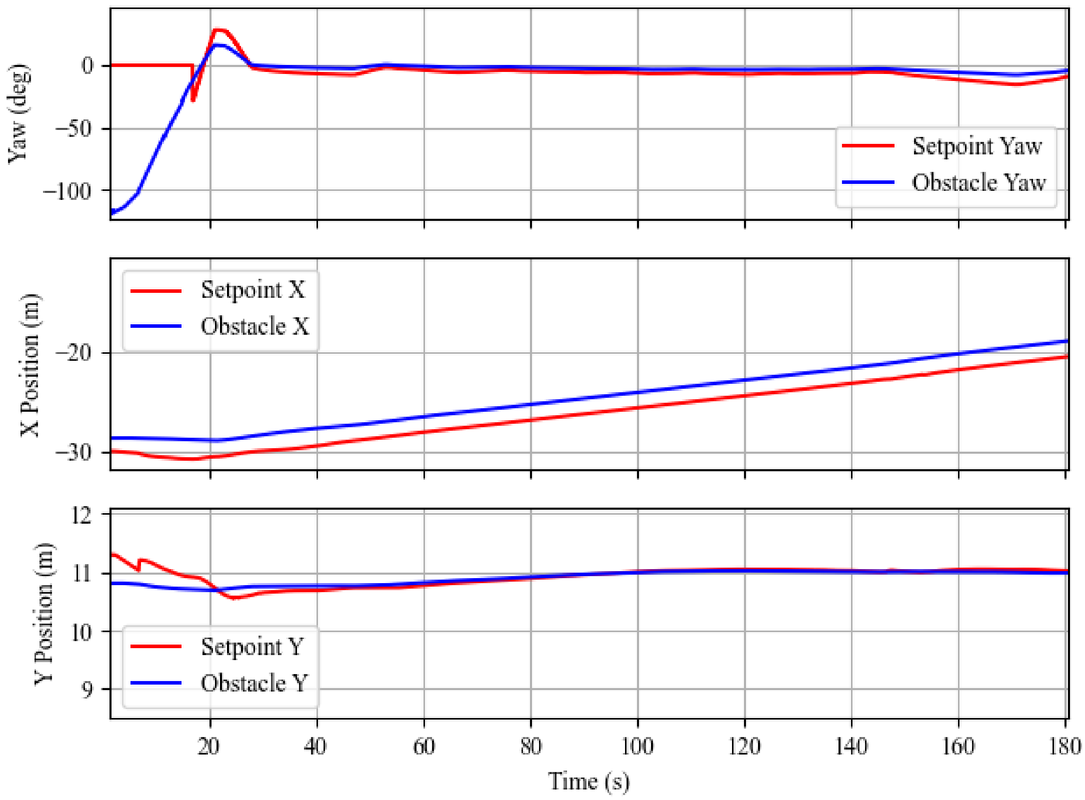

Figure 6. Time series plot of Setpoint (ship desired position) and Obstacle positions and orientations during straight path following maneuver in the experimental basin.

CONCLUSIONS

The results of this study demonstrate that the proposed pushing-based control system provides an effective and reliable method for manipulating floating objects. The controller successfully maintains stable contact and accurately steers objects along desired trajectories, even when presented with a variety of initial conditions in both the simulation and experimental scenarios. Compared to manual control, the automatic pushing controller exhibits significant advantages in terms of precision, consistency, and reduced operator workload.

The findings indicate that this approach can enhance maritime operations by enabling conventional vessels to perform complex manipulation tasks without requiring specialized tugboat designs. Future research will focus on extending the framework to cooperative multi-ship manipulation and refining control strategies to further improve robustness under varying real-world conditions.

FUTURE WORK

For future work, we plan to use the Simulation Performance Lab for Autonomous and Stationkeeping Operations in Harsh Environments (SPLASH) to refine the controller topology for maneuvering floating objects through direct pushing. Our current studies relied on a simplified 2D simulator to assess robustness and trajectory-following performance; SPLASH offers a high-fidelity 3D environment with real-time simulations.

Future simulations will focus on optimizing control strategies to improve resilience against environmental disturbances. These efforts will contribute to more efficient maritime operations with applications in ice management and offshore maneuvering. Ultimately, the findings will guide experimental validations, bridging the gap between simulation-based research and practical deployment.

In addition, limits of controllability for non-prehensile pushing of a floating object should be explored. There are maneuverability limits to what can be achieved with a single ship pushing. Stability and convergence could also be studied for a generalization of this approach.

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