Control of a full port-to-port mission for a feeder vessel

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***Abstract*—Autonomy is posed as a solution to decrease the amount of qualified personnel on a ship. It would be especially advantageous for those tasks that are dirty, dull or dangerous. Such a solution would be a win if for those cases the available personnel can be freed and they can be employed for more interesting and challenging operations.**

We automate an operation that repeatedly sails a 71 m long feeder vessel between the ports of Pireaus and Mykonos. This is done as part of the EU MOSES project to improve the short-sea shipping services. Although sailing port-to-port mainly consists of tracking waypoints, there are other tasks to consider, such as docking and undocking. We split the full operation into several subtasks that we solve separately. Each of these tasks consist of a (time-dependent) target and a vehicle controller. These tasks are combined to perform the whole operation. These individual tasks can be used to build upon in other future operations.

Simulations show the correct working of the different target-generators with controllers in their individual task. Switching between the tasks is done without discontinuities in the output forces and torques. With these results, the next step will be to perform the port-to-port sailing in our basins.

***Index Terms*—Autonomous surface vehicles, automatic docking, control switching, mission simulation**

I. INTRODUCTION

Autonomous shipping is not only limited to moving a ship through the seas. Other tasks such as docking, sailing in a harbour and Dynamic Positioning (DP) station keeping can be part of the full mission too. The mission, or operation, consist generally of a succession of tasks. In the EU MOSES project we aim at automating an operation that repeatedly sails a 71 m long feeder vessel specifically designed in this project between the ports of Pireaus and Mykonos. The MOSES projects aims to significantly enhance the short sea shipping component of the European container supply chain [1]. Other elements in the project are a self sufficient robot container handling system and a digital collaboration and matchmaking platform.

Although sailing from port-to-port mainly consists of tracking waypoints at open water, there are other tasks to consider. The operation to sail from one quay to the next can be decomposed into several tasks [2], [3]: i) open-water sailing, ii) decelerating and alignment to the dock at a small but safe distance, and finally iii) slowly moving the ship against the fenders. We consider undocking as a symmetric task of docking, and is not considered as a task on its own in this work. These phases are illustrated in Fig. 1.

The objective of this work is to simulate the full operation to sail from Pireaus to Mykonos. We approach this by solving the individual tasks, and combine them again such that we can successfully automate the trip. The individual solution can be re-used to automate other future missions. In this paper we will validate the results in simulation before it is applied to model-scale hardware and future demonstrations. Collision avoidance is outside the scope of this work, and we assume that we obtain measurements of the ship state of good enough quality.

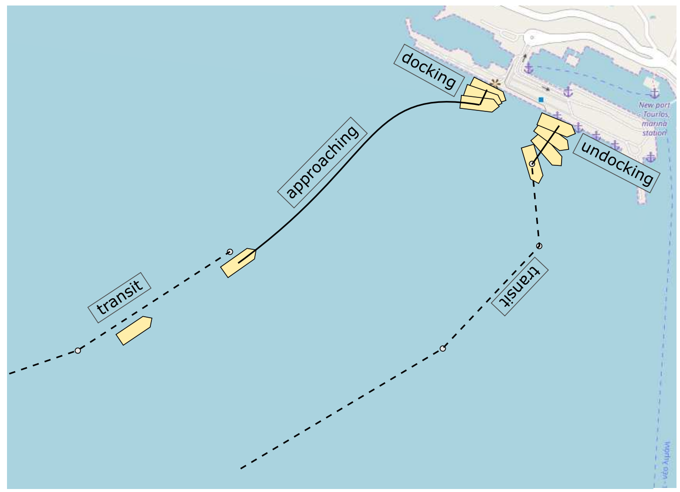

Fig. 1. Decomposition of the port-to-port mission into several phases. The emphasis in this figure is on the docking part of the voyage.

The paper will start by providing the simulation framework in section II in which we will test the controllers. The design of the trajectories and controllers is elaborated upon in section III. The results of the simulations is treated in section IV. We will finish with our conclusions.

II. SIMULATION FRAMEWORK

A detailed numeric model based on manoeuvring coefficients is available in our simulation environment. Detailed information on the simulation framework and its configuration for this study can be found in [4], [5]. A schematic representation of the feeder vessel used is shown in Fig. 2. It is a 71 m long feeder vessel with a beam of 13 m and a 4.5 m draught. The behaviour of the actuators as well as their limits, the hydrodynamic interaction due to waves and current, and other environmental forces, such as wind forces, are calculated and incorporated in the simulation framework. The ship itself is course unstable.

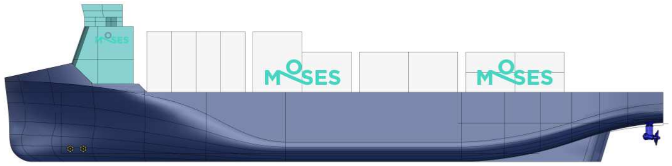

Fig. 2. Feeder vessel used in this study

The ship has two bow tunnel thrusters and two azimuthing thrusters. The bow thrusters' effectiveness decreases at larger surge speed. When the speed get larger, $u > 1$ m/s, the bow thrusters are no longer used, and the azimuthing thrusters are coupled, e.g. they are provided the same setpoint for the RPM and their angle. This means that above this speed the system becomes underactuated: there are more degrees of freedom than there are actuators. For smaller speed, when the bow thrusters are effective and the azimuthing thrusters are decoupled, the system is overactuated. An allocator algorithm is used to map the forces and torques requested by the vehicle controller to these actuators such that the total amount of power is minimal.

A state machine dictates the operation. It activates the correct controller and allocator for the phase of the operation we are in, and it also provides appropriate parameters, such as the target positions or a set of waypoints, to the controller.

III. Control

A controller with an accompanying setpoint generator needs to be designed for each of the tasks. For ease of notation the combination of a controller with its setpoint generator is often referred to as a controller in this work. At the beginning of each task the controllers need to be initialised to get a smooth transition. The general approach for this is treated before the actual controllers are treated.

A. Smooth transitions

When the individual tasks are combined to shape the whole operation, switching the controllers should not introduce excessive transient signals. We do not want to be dependent on the internal working of the controller and its coefficients for a smooth transition between the tasks. Fig. 3 depicts our approach to get continuous signals at switching times.

Only one controller is active in each phase. This is chosen such that there cannot be multiple controllers active that might oppose each other. Furthermore, in the future the amount of tasks will be extended, and correspondingly the number of controllers. It will save on computational resources if we only need to calculate the output of one controller. Let Fig. 3 illustrate the controller that just became active. It receives a setpoint (SP) and measured value (MV) from somewhere else, this might be, for example, the location of the dock, and depends on the task at hand. For each controller it will be treated in the next subsection.

A signal, Δ_{sp}, is added to the setpoint that goes to zero in a fixed amount of time. This signal is chosen such that the

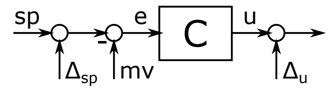

Fig. 3. Scheme used to smoothly transition between controllers. The signals Δ_{sp} and Δ_{u} vanish in time, make the control signal continuous.

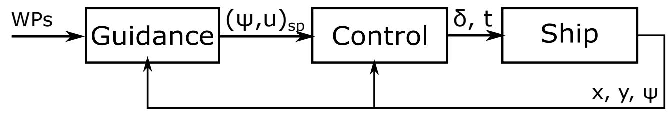

Fig. 4. Guidance-Navigation-Control framework used for underactuated vessels. The navigation block is omitted under the assumption that we measure the position and heading.

error to the controller starts at zero at switching time $t = \tau$, e.g. $\Delta_{\mathrm{sp}}(t) = (\mathrm{MV}(\tau) - \mathrm{SP}(\tau))\, P(t - \tau, T_{\mathrm{e}})$, where P is the polynomial $P(t, 1) = 1 - 10t^3 + 15t^4 - 6t^5$ that goes from one to zero and has zero first and second derivatives. Next to a change in the setpoint, a similar signal is added to the output. Again, this signal is selected such that it goes to zero in a fixed time period, and that the initial output of the controller equals the output of the control signal before the switch: $\Delta_{\mathrm{u}} = (u(\tau^-) - u(\tau^+))\, P(t - \tau, T_{\mathrm{u}})$. These choices make the control signal continuous, but not necessarily differentiable. The signals introduced to get a smooth transition can be seen as finite disturbances that disappear in time. A *linear* controller can therefore not be destabilised by it.

B. Controllers

1) transit phase: In this phase the ship sails a path defined by a set of waypoints while only the thrust and angle of the coupled azimuthing thrusters are used. The bow thrusters are not effective at cruising speed. This makes it an under actuated system. The Guidance-Navigation-Control (GNC) framework, as illustrated in Fig. 4, is used to cope with this [6]. In the GNC scheme the navigation block estimates the pose of the ship. This is not used in this study as we assume that the pose is measured, and hence it is omitted from the scheme. The guidance block has to convert the list of waypoints with latitude/longitude and speed to a setpoint for the heading and speed which, in its turn, the vehicle controller can track. At the activation of the transition phase the signal Δ_{sp} will be started at the difference of the measured heading and heading setpoint from the guidance, and the same holds for the speed.

The required heading result from a Line-Of-Sight (LOS) guidance algorithm [7]. The specific LOS algorithm used adapts the look-ahead distance based on the distance between the path and the ship, known as the cross track error. The results is that the heading setpoint points the ship more directly to the path for larger cross track errors, while close to the path it looks further ahead to minimise setpoint oscillations. The speed setpoint is copied from the speed provided by the user between the waypoints.

When the transit controller becomes active, it looks for the segment that is closest to the ship and starts tracking it. When it passes the last waypoint, it indicates this to the mission execution such that the state machine can move to the next phase in the operation.

The heading provided by the LOS algorithm is tracked with a stateless PD controller. When the rate-of-turn and the heading are measured, then we can use a pole-placement approach to have the closed loop behaviour mimic a critically damped second order system under the assumption that the dominant dynamics behave as a first-order Nomoto model [8]. The natural frequency of this second order system is increased until the limits on the rudder rate-of-change is reached during open sea conditions.

The ship used is course unstable, see for more information [9]. Such a system can be controlled with the above mentioned approach, but care should be taken that the derivative action should be large enough [10].

The speed is tracked with a PI controller with feedforward. Again, pole placement was used to calculate the gains: the relation from thrust to velocity is dominantly first-order. The steady state relation between the thrust and velocity is used as feedforward signal. The feedforward component is found to be responsible for the majority of the control signal. On activation of the speed controller, next to using the approach shown in Fig. 3, the I-action is reset to zero.

2) approaching phase: During the approaching phase, the vessel has to move from the initial pose and velocity to a safe distance from the quay and arrive there with zero velocity. At the start of this phase, a Bézier curve is constructed that smoothly connects the position and heading at the transition time, to the required pose at a safe distance from the quay. Furthermore, a mapping from time to the Bézier path variable is made to convert the path to a time-dependent trajectory. The velocity at the start of this phase, and the zero velocity at the end are used as boundary condition [11].

During the approaching phase, the speed and the course change significantly. The approaching phase is split for control purposes into two parts: the first without, and the second with effective bow thrusters, i.e. a switch form underactuated to fully actuated.

At higher surge velocity the bow thrusters are not effective. The GNC framework, Fig. 4 is again used. The input to the guidance is not a list of waypoints, as indicated in the figure, but the Bézier based trajectory. A Constant-Bearing (CB) guidance algorithm is used to translate the required time-dependent longitude and latitude to a required heading and speed [12]. This guidance is used since we want to track a time-dependent trajectory, and not a path as in the transit phase. The CB algorithm calculates a velocity vector such that the vessel moves in the direction of the latitude/longitude requested, and adds the velocity setpoint to it. The resulting vector is then converted to a heading and speed that the underactuated vessel can track. The vessel's trajectory will converge to the trajectory required.

The vehicle controller is a cascade course controller that uses the known system dynamics in a feedforward controller, and a feedback controller to counteract disturbances [9]. The gains are speed-dependent to cope with the change in dynamic behaviour which changes in the surge velocity.

At lower speeds the bow thrusters are effective and the system can be considered fully actuated: the GNC framework is no longer needed. The same trajectory as above is tracked, but the pose is directly provided to three independent PID controller, one for each degree of freedom in the horizontal plane: (x, y, ψ). At these lower speeds, the coupling between the degrees of freedom is ignored, and the vessel is considered as three independent moving masses. The gains can then again be calculated such that the closed loop behaviour mimics a second order system.

Although the previously calculated trajectory is reused, the pose when the second part of this phase is started was not likely to be perfectly tracked. The difference between the actual and the required pose is added such that the controller starts with a zero error. This signal is decreased to zero as indicated before. An offset is also added to the control signals. The result of this is illustrated in Fig. 7. When the reference signal reaches its end, the controller indicates that it has finished and the next phase can be started.

3) (un)docking phase: The final phase to reach the quay is the docking phase. At the start of this phase a trajectory is constructed that connects the initial pose to a pose against the quay. The trajectory is a polynomial interpolation for each of the degrees of freedom. An equal PID controller as for the second part of the approaching phase is used. Although it can be tuned differently, this is not done in our simulations. The trajectory starts at the current position, so there will be no initial error. An additional control signal is used to avoid jumps in the control signal.

Although not of any influence on the control behaviour, the measurements for this phase are not with respect to a global earth fixed coordinate system, i.e. GPS. But the coordinates used denote the position of the dock in a camera based coordinate system that is connected to the ship. Reliable position and heading measurements are of vital importance during the docking procedure. The use of a relative position and heading measurement is expected to be more accurate and more reliable than a global position measurement.

4) docked phase: The ship will be stay docked in the simulation by means of its thrusters. A position setpoint is provided to the DP system such that the fenders are compressed to a specific pre-tension. This will avoid the use of mooring lines, but might be only applicable for shorter times.

IV. Results

Fig. 5 shows a still from the simulation of the port-to-port mission from Pireaus to Mykonos. The distance between the ports is shortened in this work. This still is taken at the beginning of the docking phase in Mykonos. Some of the signals from this simulation are shown in Fig. 6. The vessel starts at $(x, y) = (0, 0)$ in a docked situation at the port of Pireaus, best seen in subfigure a). After undocking it starts sailing the path that is defined by the user through a set of waypoints.

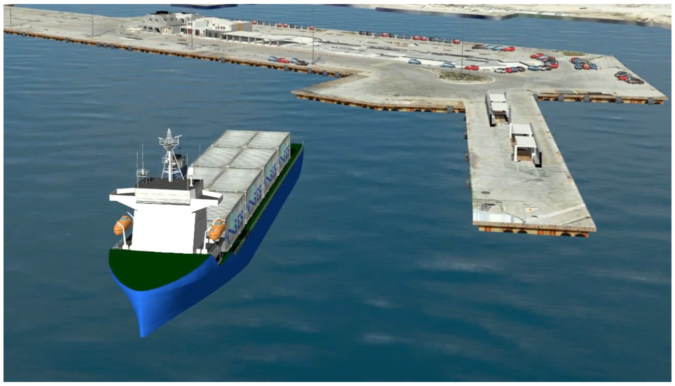

Fig. 5. Still from the simulation in the docking phase. The vessel is moving slowly from its safe position to the dock.

The vessel starts the approaching phase at $\tau_1 = 5691$ sec at position $(x, y) = (4490, -1975)$. At $\tau_2 = 6061$ sec the surge speed has become less than one meter per second, and the bow thrusters can be used. The pose of the vessel is shown in the inset of Fig. 6a). Note that there is a small drift angle; we control the course on-ground, not the heading. It takes until $\tau_3 = 6551$ sec until the vessel is at the safe position without any velocity. From that time onwards it moves slowly sideways and rotates to align with the quay until it touches the fenders as shown as the top of the figure. From $\tau_4 = 7151$ sec till $\tau_5 = 7451$ sec the vessel remains docked. After this, it undocks to a safe pose again, and finally, at $\tau_6 = 8052$ sec it starts to track another set of waypoints back to Pireaus. The surge velocity and rate-of-turn are shown in Fig. 6b) and d). In Fig. 6c) and e) the required forces and moment are plotted. Although not shown here, we use an allocator to map these forces to the thrust and angle of the different actuators.

The operation is simulated in a single run. The different phases have different trajectory generation, guidance algorithms or vehicle controllers active, and the state machine switches between them in the simulation. All the individual components behave as required, and when switching from one to the other, the output does not jump. However, there are fast derivatives when the next phase is entered. When the vessel is sailing back to Pireaus at $t = \tau_6$ the acceleration is large, and a high peak is seen in the forward thrust requested.

From $t = \tau_3$ onwards the vessel is moving from a safe position in the direction of the quay. Just before it gets into the 'docked' state, it connects with the fenders. The fenders do have some compliance, but in Fig. 6 this contact moment is clearly visible. The ship tries to reach the pose specified with its controller such that a specific fender load is achieved. Even after it is docked, there is interaction between the quay and the control system of the vessel. In practice this is not seen as a point of concern; at that time mooring lines will be connected and the control system will get to an idle state.

Fig. 7 shows some zoomed signals during the approaching phase. Subfigure a) shows the path of the vessel. The black dotted line shows the Bézier curve that connects the start pose of this phase to the safe pose close to the quay. The blue line, until $t = \tau_2$, shows the part without bow thrusters. The bow thrusters are active in the second part of this trajectory, from $t = \tau_2$ to $t = \tau_3$. During the first phase the vessel cannot track the trajectory spot on. The velocity is low, and it has to change it's course significantly. When the bow thrusters become active, then the system is fully actuated, and the trajectory can be tracked. The difference between the actual position and the required position is added to the function Δ_{sp}. The resulting transition goes smoothly. The same effect can be observed in Fig. 7b). It shows the RPM of the azimuthing thrusters and the RPM of the bow thruster. It can be seen that the bow thruster is not active until $t = \tau_2$, and that the transition when it becomes available is smooth. It is interesting to see how the bow thrusters do give a big push to get the vessel on the specified trajectory. Fig. 7c) shows the angle of the azimuthing thruster.

In Fig. 7 the gray line indicates the values when there is a wind of 10 m/s and the waves are generated from a JONSWAP distrubution with $\gamma = 3.3$, a significant waveheight $H_{\text{s}} = 1.0$ m, and a peak period of $T_{\text{p}} = 10.0$ s. The trajectory that it tries to follow deviate from the undisturbed version, as the initial pose is different. The actuators oscillate in correspondence with the waves. Thee results are considered more than sufficient. If the response to the waves is considered too much, a wave filter can be included .

V. Conclusions

The objective of this work was to simulate the full operation to sail from the port of Pireaus to the port of Mykonos and back again. This has been done successfully through a divide-and-conquer approach.

A set of controllers with an accompanying reference generators were developed. Switching between them is done with a state machine and with this we could simulate the full mission. This allows to focus on testing complex missions in simulation and design configurable, re-usable components before they are tested with hardware. The next step is to perform these tests in our basins.

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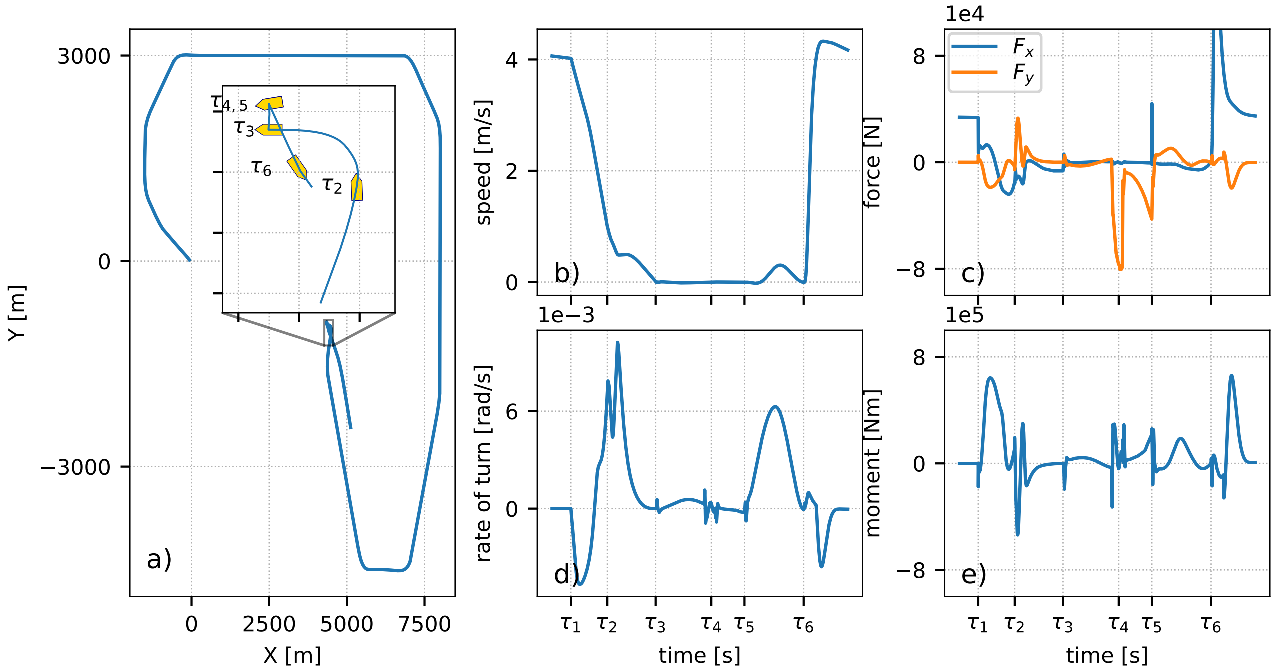

Fig. 6. Simulating the port-to-port mission from Pireaus at $(x, y) = (0, 0)$ to Mykonos at $(x, y) = (4300, -900)$. Times are defined as τ_1: start approaching, τ_2: bowthrusters active, τ_3: start docking, τ_4: docked, τ_5: start undocking, and τ_6: start transition. The time traces in b) till e) show slightly more than 3350 seconds. a) shows the path that is sailed, with a zoom of the docking manoeuvre in the inset. b) and d) respectively give the surge speed and rate of turn. c) and e) depict the forces the toques that are requested during different phases.

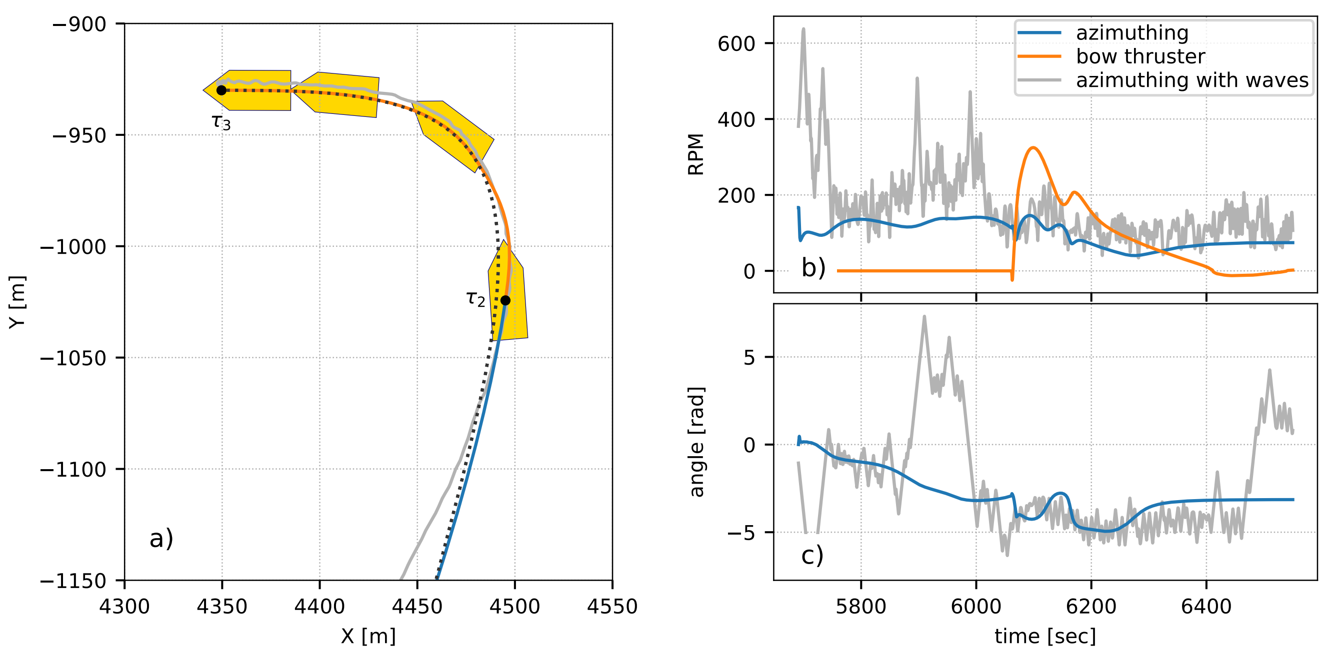

Fig. 7. The left-hand side shows the path during the approaching phase. The dotted line is the initially calculated Bézier path. The orange/blue line show the part with/out bow thrusters. The gray line shows the path with environmental disturbances. A different initial condition will provide a different trajectory. The right-hand side shows some actuator signals.

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