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Trickle-down strategies: integrating simulations with control loops of autonomous vessels on lab scale

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Abstract. This study integrates strategic decisions and operational control systems in autonomous shipping. By providing ships with situational information and adding a virtual operator, we show that vessels can make informed choices regarding their route and engine settings. To demonstrate this integration, we developed new components and put these to the test in three lab experiments.

The *green routing* capability experiment showed the bridge between the control system of the autonomous vessel, operated via Robot Operating System (ROS), to the simulation environment of OpenCLSim. We developed a real-time variant of OpenCLSim and a communication component that could expose the state of the OpenCLSim simulation with the ROS system. This experiment showed that an autonomous vessel could follow a path provided by the simulation.

The *green steaming* capability experiment showed that the ship could also adapt its speed based on information from the simulations. We developed an additional communication component capable of advising the vessel about its velocity. Together with the green-routing capability, this forms the basis for more complex experiments.

The *port layout* experiment showed a potential use case of the green-routing and green-steaming capabilities. We created a waypoint layout similar to the port. While a ship is sailing, twelve simulations are computed every five seconds. The scenarios vary in engine order, route choices, resulting in varying emissions, fuel, and cost. We evaluated the impact of different tactics such as green-routing, green-steaming, and full-speed sailing on operational behavior like steering and engine order. Our approach, using a real-time version of a Vessel in the OpenCLSim simulation software, enabled predictive simulations to facilitate the chosen tactic based on a given strategy. Integrating simulations to evaluate the options with the control systems can develop into a valuable tool for optimizing vessel performance and reducing environmental impact in autonomous shipping operations.

1. Introduction

As we work towards reducing climate change and cleaner air, using existing and future energy sources efficiently becomes essential. The Green Deal [1] states that the shipping industry should contribute to these targets as an alternative modality (cleaner than transport over road) and by reducing the emissions of shipping itself. The reduction of emission from shipping with 50% in 2050 was supported by International Maritime Organization (IMO) [2]. Fossil fuel sources need to be used more efficiently to reduce emissions. New energy sources, such as batteries, can help reduce emissions but also reduce the range of vessels. Thus, it will become more important to facilitate ships in route or engine setting choices.

Choosing whether to sail based on minimal emissions, maximum fuel use, or earliest arrival time is a strategic decision. A ship can change its course or engine order based on these goals. Optimizing engine settings to arrive just in time can save up to 10% of fuel [3]. Depending on route choice and optimal engine settings, a ship can try and follow these, considering currents, other traffic, infrastructure, and tidal windows. Suppose the strategy (reduce emissions) results in operational actions (reducing engine power when possible, steering in a direction that results in less fuel use). In that case, the strategy has trickled down into the operation.

A ship needs more situational information to decide the optimal engine settings and direction. This information needs to be processed by the captain or, more and more often by partial or fully autonomous systems [4]. In this research, we focus on the question on how to provide situational awareness to autonomous ships. How can we help autonomous ships to take tactical decisions (green steaming or green routing) based on a strategic goal (less emissions or optimal sailing time)? We focus our research on the lab scale to make the research reproducible in a controlled environment. Here we use the concept *green steaming* to refer to the optimal engine setting to reduce emissions. We refer to *green routing* as the concept to optimize the route or number of port calls to reduce emissions [see also 5].

2. Experiments and methods

To answer the question of whether we can help autonomous ships make choices about green steaming and green routing based on strategic goals, we make use of a lab environment and simulation software. We combine these in experiments which build up towards the integration of these concepts.

2.1. Lab

For this research, we make use of the facility at the Research lab Autonomous Shipping (RAS) lab [see e.g. 6] of Delft University of Technology. Autonomous ship research has been receiving increasing attention of the last decade, with research moving from theory towards practice using a range of scale-model vessels . In this research we use the autonomous vessel Tito-Neri. The autonomous vessel and the outdoor facility (a small pond) are displayed in fig. 1. The Tito-Neri ship is a scale-down replica of the actual tugboat bearing the same name. It measures 1.45 meters in length, weighs 16 kg, and features a mono-hull design. The average speed of the vessel varies between 0.1 to 0.6 m/s.

The ship is equipped with accelerometers, encoders, distance measurement sensors, gyro, and Global Navigation Satellite System (GNSS). An Real-time kinematic positioning (RTK) GNSS receiver is positioned near the pond. This receiver significantly improves the GNSS signal of the Tito-Neri, ensuring better operation.

The ship uses a wireless network connection for communication. A bow thruster and two azimuth propellers provide the ship's physical control. We use the Robot Operating System (ROS) system [7] to communicate with the ship. The ship is steered using control software on an Arduino board. The Arduino board communicates with an onboard (of the ship) Intel NUC computer.

2.2. Software

To support the autonomous ship, we extended the list of supported controllers with a velocity controller. The autonomous vessels work with an reference quantity (Set Point (SP) in control theory) and a measured quantity (Process Variable (PV)) and a quantity that can be influenced (Manipulated Variable (MV)). The ship can control its Revolutions Per Minute (RPM) (MV)

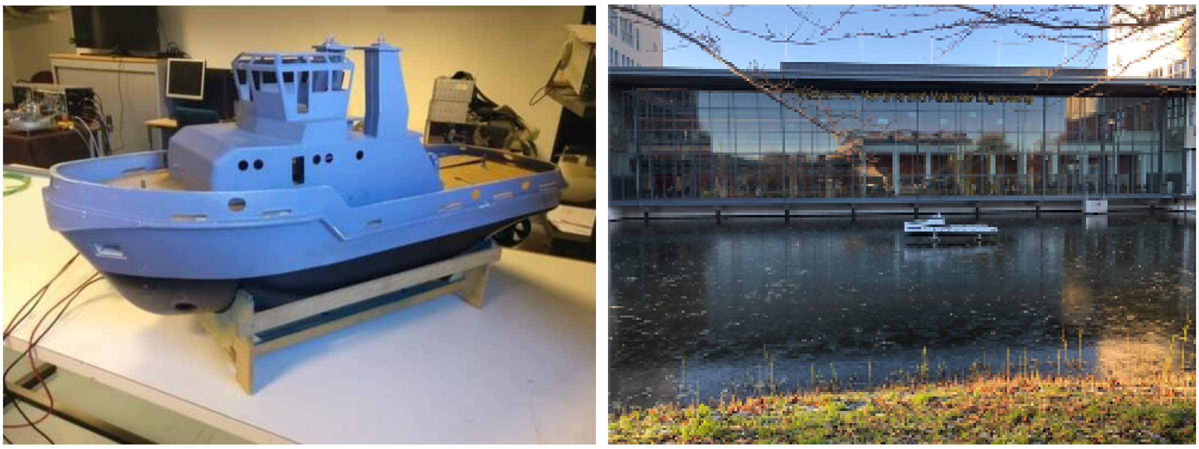

Figure 1. The ship Tito-Neri [left, 6] and pond (right) that were used for this experiment.

using a Proportional–Integral–Derivative (PID) scheme. It observes the measured velocity (PV) and tries to meet the reference velocity (SP).

While the real ship is sailing, we mirror the ship with a virtual clone. We create a virtual vessel using the OpenCLSim [8, 9] and OpenTNSim [10] software. The OpenCLSim software provides the core component for the virtual clone of the ship. The OpenTNSim software supports the route bounded sailing. The energy module [11] provides support for calculating emissions. We can link the virtual clone and the real world using mixins that receive messages from the real world and update the active state. The virtual ship can send back route and engine order advise to the real world. We used the ROS communication bridge as the message hub. The software is available in the OpenTNSim github repository [10].

2.3. Experiments

The *green-routing capability* experiment shows the bridge between the control system of the autonomous vessel, operated via ROS, to the simulation environment of OpenCLSim. For this experiment a circular network in the pond was created. The ship was informed of the next waypoint. The ship sent it's current Global Positioning System (GPS) signal back to the simulation. The simulation then determined which nodes on the circular network had been sailed through. After a node was reached, the next node was announced. The ship would use its heading control to reach the waypoint.

The *green-steaming capability* experiment showed that the ship could also adapt its speed based on information from the simulations. We developed an additional communication component capable of providing the vessel with a reference velocity. The same circular layout as in the green-routing experiment was used. Now the ship was informed of a reference velocity. This reference velocity was announced on a new ROS channel. When the ship sailed the southern part of the circle was advised to follow the low velocity. The northern part of the circle the ship was advised to sail at full speed.

The *port layout experiment* intends to represent a potential use case for green-routing and steaming capabilities. A ship is assigned a strategy, which can be one of lowest emissions, or lowest sailing time (table 1).

A virtual second ship is introduced that can or cannot occupy a berth. This berth is one of the waypoints along the route. While a ship is sailing, twelve simulations are computed every five seconds, by a virtual operator. The scenarios vary in engine order, and route choices, resulting in varying emissions, fuel, and cost. Based on the strategy a ship can decide which of these options

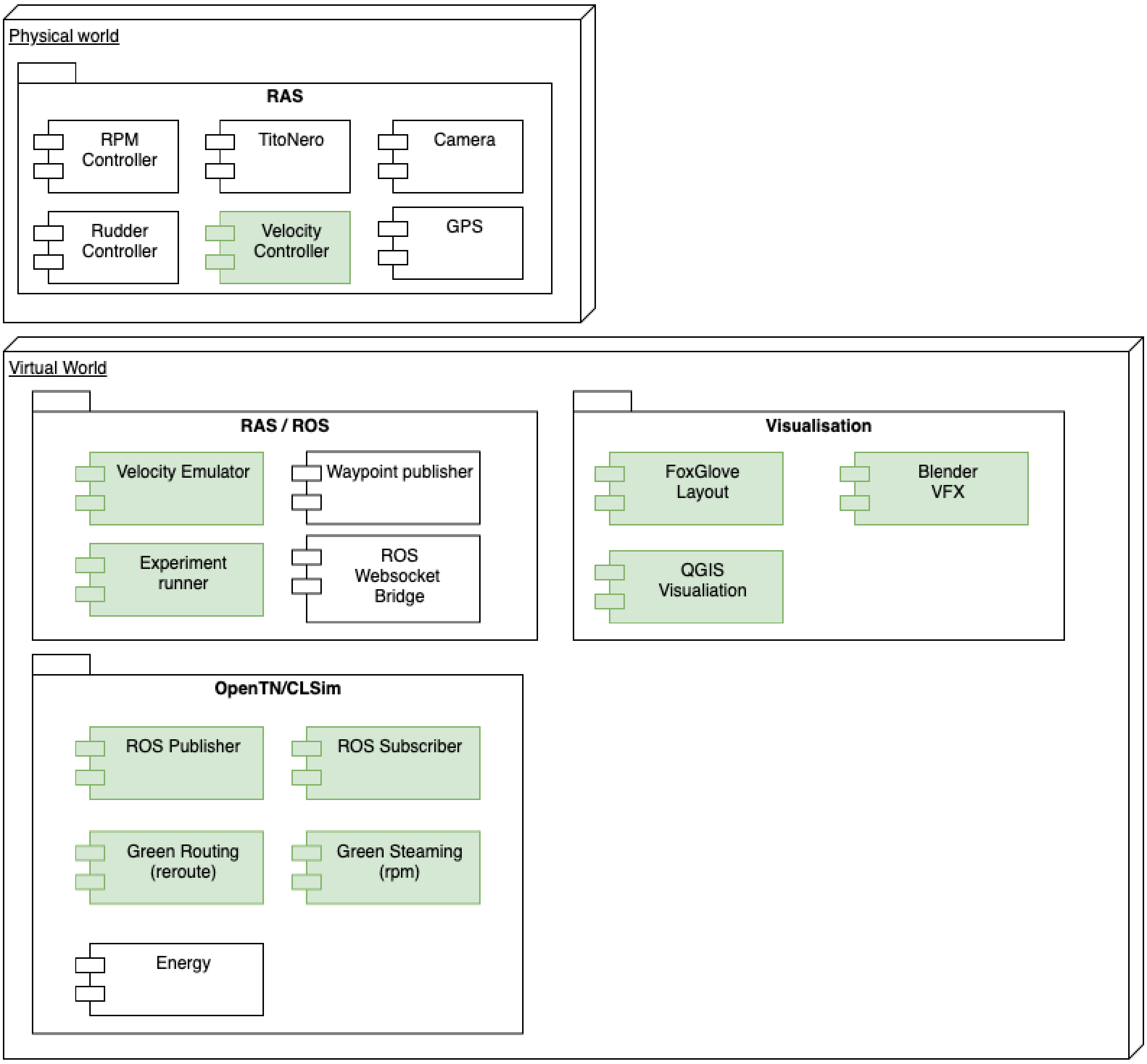

Figure 2. The existing (white) and developed (green) software components used for this experiment.

to pick. To represent real-world emissions of a typical inland ship the emissions were calculated using a prototype large Rhine Vessel, Classification of European Inland Waterways (CEMT) class Va [11].

Scenario	Strategy	Berth available	Chosen tactic
Case 1	Reduce emissions	Unavailable	Green steaming + routing
Case 2	Reduce emissions	Available	Green steaming
Case 3	Reduce time	Unavailable	Green routing
Case 4	Reduce time	Available	Full speed

Table 1. Experiment 3: four scenarios used to test tactic chosing capability

To port layout experiment is based on a real-life logistics scenario. The scenario involves transporting goods between the BCTN terminal in Alblasserdam, the Cetem Containers terminal near Spijkenisse, and the ECT Terminal at the Maasvlakte. The route was created using the Fairway Information System [12]. In scaling down the scenario for the lab-scale experiment (fig. 3), the primary objective was to retain the essential aspects of the logistics process. The essence of the experiment was defined as the transportation of goods between three terminals, with the middle terminal located approximately halfway between the other two.

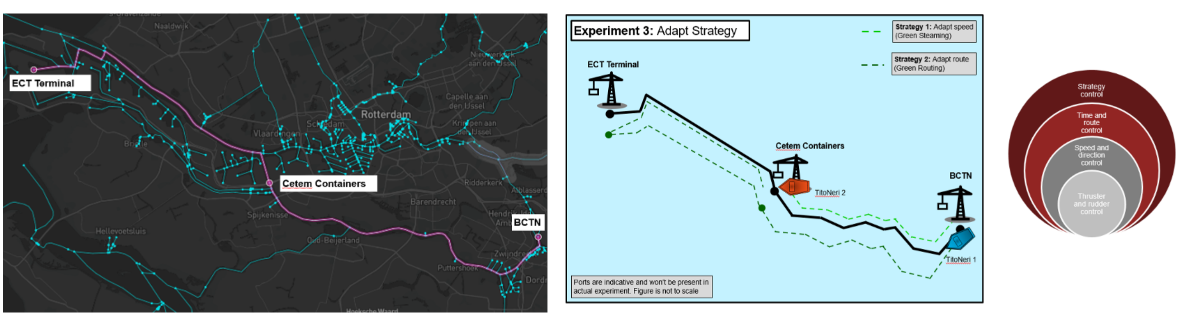

Figure 3. The real-world port layout (left) and the schematic representation in the pond (right).

2.4. Analysis methods

To analyse the results, we compared the reference path and velocity to the expected reference paths and velocities. We used Bagpy, Pandas and Foxglove to analyse the results. We used the QGIS, Blender and Matplotlib software to visualize the results. The dataset of the experiments include bag files with time series and recorded videos made available at the Zenodo archive [13].

3. Results

We focus on the results of the port layout experiment. This experiment integrates the capabilities of the green-routing and green-steaming experiment (experiment 1 and 2). The collected data included the following key components:

Observed vessel positions The position over time of both the physical and the virtual vessels was recorded, providing insights into the spatial dynamics during the experiment.

Reference position and velocity The ship was informed of a reference velocity and route. Reference in this context refers to the advisories that it got based on the OpenCLSim simulations. The predetermined trip that the vessels were intended to follow was recorded. This data allows for assessing adherence to the planned route and any deviations that may have occurred.

Berth availability The availability of the berths, and designated areas for vessels to dock or anchor was recorded. This information is relevant for understanding the logistics scenario and evaluating the automated response to berth availability.

For each case in *port layout experiment* the simulation calculates the total duration of the voyage. The GNSS traces of the four cases that we tested (presented in table 1) are shown in fig. 4.

It can be seen fig. 4 that the ship took a detour in cases one and three. This shows the capability to take detour based on an emission optimization. This is what we refer to as green-steaming capability. In cases two and four the vessel sailed the direct route.

It can be seen fig. 5 that the ship sailed at lower velocity in cases one and two. This shows the capability to use the *green steaming* tactic.

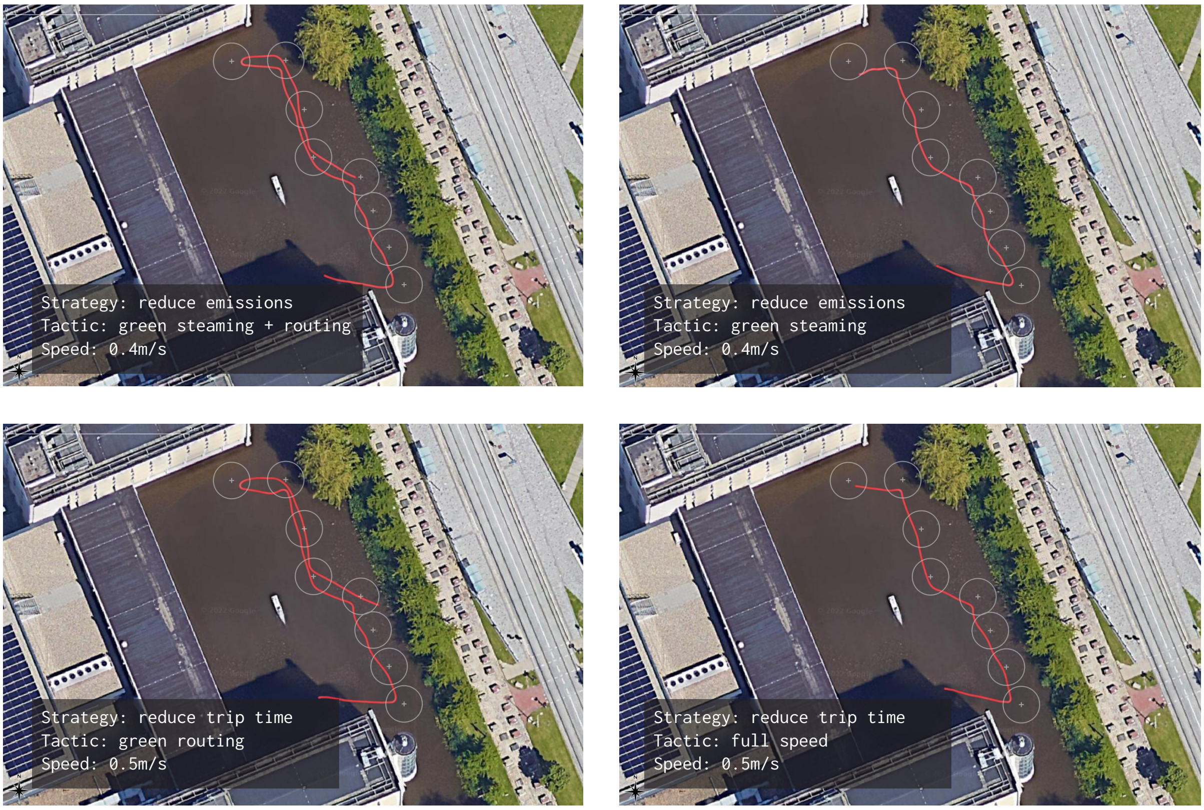

Figure 4. The route followed by the vessel during the Port Call experiment for the four cases (up: case 1 and 2; down: case 3 and 4). Red line presents the sailed path.

4. Discussion and conclusion

This study shows, using experiments on lab scale, that it is possible to support autonomous vessels in their route and engine-setting tactics. With this research we aim to provide a bridge between ambitions set at a high level and practical operation. When you set a high-level ambition, such as to reduce emissions through or by changing more transport to the inland shipping modality, it will work if not only the ambition is shared from policy to practice, but if the actions also are optimal from the perspective of an individual ship. To achieve this one needs to align ambitions between multiple levels [see e.g. 14].

Another challenge arrives when one of the actors in the system is no longer human. In our experiment, this is the operator of the ship. In autonomous shipping, we have to make sure that the ambitions from higher levels of governance, such as rules, regulations and, in our example the ambition to reduce emissions, also trickle down into concrete actions in the steering hut. In our example, we showed that, at least from a technical perspective, this is also possible. The next steps in the research, in the larger Path2Zero project, aim to develop these efforts into actionable information for inland ships using real-world data for both autonomous and non-autonomous vessels.

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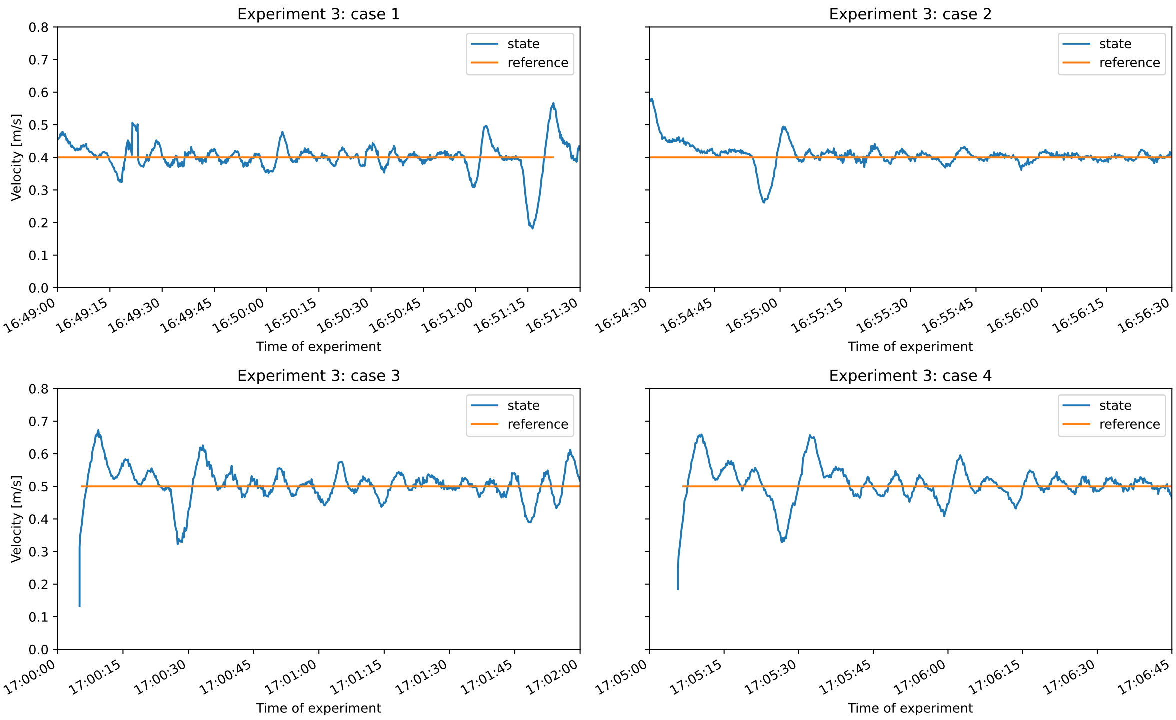

Figure 5. Reference and state velocity of the Tito Neri for the Port Call experiment (Strategy: Time, Berth available: True, Alternative for the four cases. Reference velocity is the advise given based on the chosen tactic (green steaming: 0.4 m/s, full speed: 0.5m/s). The state velocity is the speed over ground that the ship sailed. A simple control mode was used to follow the reference speed.

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