SciPPPer: Automatic Lock-Passage for Inland Vessels – Practical Results Focusing on Control Performance

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Abstract. Navigating through locks is one of the most challenging tasks that skippers have to perform in inland navigation. Typical dimensions of a ship (width = 11.45 m) and a lock (width = 12 m) result in an error margin of less than 30 cm to the left and to the right of the ship when navigating within a lock chamber. Typical inland vessels on European waters have a length of 82 to 186 m. The wheel house on cargo vessels is located close to the stern of the vessel. This leads to low visibility of the bow in the lock chamber. In order to cope with this issue, a deck hand monitors the bow and announces distances to the skipper via radio. The quality of this information depends on the deck hand's ability to judge distances correctly and is prone to error. This highly demanding maneuver needs to be performed up to 15 times per day. Each lock passage can take up to 30 minutes. The research project SciPPPer aims at automating this complex navigational task.

The German acronym SciPPPer stands for Schleusenassistenzsystem basierend auf PPP und VDES für die Binnenschifffahrt – lock assistant system based on PPP and VDES for inland navigation. The idea is to fully automate the navigation into and out of a lock using high-precision GNSS (Global Navigation Satellite System) with PPP (precise point positioning) correction data which is transmitted from shore to ship using VDES (VHF Data Exchange System), an extension to AIS (Automatic Identification System). This absolute measurement data is complemented by relative measurement data using LiDAR and automotive RADAR and fused with inertial measurement data delivered by a mechanical gyro system. Apart from the challenge of precisely measuring the position and orientation of the vessel within the lock chamber, the control task poses an interesting problem as well. This contribution introduces both, the measuring and the control problem. However, the focus lies on the results of the control performance that was achieved on a full-bridge simulator as well as during real-world trials. A full-bridge simulator was used in order to test the control strategy and its algorithms safely. A number of different actuator configurations were investigated. Typical inland cargo vessels use one or two propellers with Kort nozzle and a twin rudder behind each propeller and a 360° turnable bow thruster. Typical inland passenger vessels use several (2–4) 360° turnable rudder propellers as main propulsion as well as a 360° turnable bow thruster or a classical tunnel thruster which can only apply forces to starboard or portside. These typical configurations were examined by simulation. The real-world trials were performed on a passenger vessel with three rudder propellers as main propulsion as well as a classical tunnel bow thruster acting left and right.

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This contribution presents the results of the simulator study as well as the real-world trials in terms of control performance. It explains specific challenges due to the navigation within an extremely confined space. The contribution concludes with lessons learned as well as an outlook focusing on the potential of the introduction of such a system to the inland navigation market.

Keywords: Automation · Automatic lock-entering · Navigation · Control · Smart systems

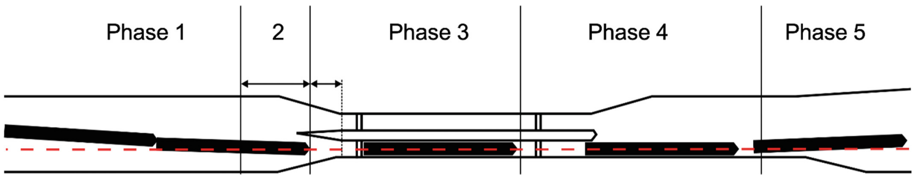
1 Introduction

The project SciPPPer aims at automating the whole navigation task of passing a lock. It is comprised of several distinct challenges which are addressed within different work packages. The main aspects are the following:

1. Requirements and System Architecture
   The overall system is analyzed. Requirements for the individual components are determined. The architecture of the assistant system is developed in form of functional subsystems. The interfaces the subsystems are defined. In order to test the whole integrated system with all of its modules, a validation and demonstration concept is established.
2. Land-Based Technologies
   GNSS (Global Navigation Satellite System) is used whenever available during the lock passage. Due the extremely confined space, centimeter precision GNSS is necessary. Instead of using the well-established RTK (Real-time Kinematics) reference data, PPP (Precise Point Positioning) is investigated within this project. PPP data can be transmitted via broadcast with the same data for all receiving parties whereas RTK is calculated and transmitted to each vessel individually. The fact that broadcast is possible as well as the fact that the required data to be transmitted for PPP is a lot smaller than for RTK, this enables transmitting PPP correction data through VDES (VHF Data Exchange System), an addition to the well-known AIS (Automatic Identification System). PPP via VDES is established within SciPPPer for the first time as a means to enable centimeter precision together with integrity monitoring on several levels.
3. Communication
   In order to transmit the PPP data as well as data about the state of the lock (i.e. lock gate open or closed), VDES is employed. Prototypical transceivers are installed at the lock and on the ship to test the real-world behavior. Since the communication is carried out next to AIS antennas the collocation problem needs to be addressed. Otherwise, the normal AIS communication would be disturbed by the transmission of VDES data in close vicinity.
4. Onboard Technologies
   The PPP data being transmitted via VDES is used on board to generate high-precision centimeter-grade position accuracy. This GNSS data is fused with inertial measurement data in order to retain position and orientation information during GNSS outages. The well-known random walk when integrating accelerations and

rotation rates limits the use of inertial measurement data to short periods of time. In order to deal with this drawback, relative measurements between lock walls and the vessel are used. Three multi-beam lidar sensors, two at the bow and one at the stern, as well as three automotive radar sensors are employed for this task. The fusion of relative lidar and radar measurement together with absolute GNSS supported by inertial measurement data is part of this work package also.

5. Maneuvering Control and Simulation
   This work package deals with the development, implementation and testing of a control strategy for the lock passage problem. This contribution focuses on this task and only touches on other aspects where necessary. In order to test in a risk-free environment, a full-bridge simulator is adapted such that it is able to mimic the real behavior of vessels during lock passage adequately.
6. System Integration and Demonstration
   All the developed components are integrated into one fully-functional prototype. Some of the developed modules such as the control algorithms are tested on the full-bridge simulator. Trials on real vessels proof that the developed prototype works in practice. Its functionality is shown in a public demonstration.



During the determination of requirements, the lock passage is divided into 5 different phases. Each phase has different requirements with respect to positioning accuracy and control performance. The 5 phases also differ with respect to sensor data availability. However, entering a lock at phase 2 is similar to leaving the lock at phase 4 whereas phase 1 is comparable to phase 5 with respect to positioning accuracies and sensor availability.

Phase 1: Approaching the lock. GNSS measurement available. Navigation radar still useful. Lidar, automotive radar not in range. Medium positioning requirements.

Phase 2: Lock chamber approach. GNSS measurement maybe available. Navigation radar not useful. Lidar, automotive radar starting to gather data. High positioning requirements for bow, medium requirements for stern.

Phase 3: Within the lock chamber. GNSS measurement not available. Navigation radar not useful. Lidar, automotive radar fully working. Highest positioning requirements.

Phase 4: Similar to phase 2. Lidar at bow may still work. High positioning requirements for stern, medium requirements for bow.

Phase 5: Similar to phase 1.

Section 1 gives a brief overview of the SciPPPer system and explains the requirements for the different sub-systems. Section 2 introduces the controller as well as the state estimator and all other functional modules that are part of the maneuvering control system. Section 3 shows the results of the full-scale trials.

2 System Overview

The SciPPPer projects comprises of land-based elements as well as onboard equipment. The communication infrastructure consists of antennas and transceivers for VDES both on shore and on the vessel. Servers on land receive PPP correction data, validate it and transmit it through the VDES communication channels. Lock status information is also processed and transmitted via VDES. The data stream is received onboard of the vessel, decoded and fed into GNSS receivers which are able to calculate centimeter-grade accuracies. The lock information is used to determine if the lock chamber is ready to be used.

Beside the GNSS compass there are 3 laser scanners (Lidar sensor) and 3 automotive radar systems to determine the relative position and orientation of the vessel with respect to the lock. One of the laser scanners is used to detect objects such as other vessels in front as well as to detect the lock gate when closed. The other two laser scanners are installed in order to find the walls of the lock chamber using a large horizontal field of view. The point clouds are processed such that the distance to the detected lock walls as well as the orientation between ship and lock can be computed.

All of this sensor information is shown to the skipper through dedicated displays. It is also fed into the control system which fuses the different sensor information into one state estimation using a mathematical ship model. The control system consists of a PLC-based processor with several interface modules which are able to read the sensor data as well as control the actuators by communicating with the propulsion control system. Several actuator configurations were evaluated. Figure 1 shows a simple overview of the SciPPPer system.

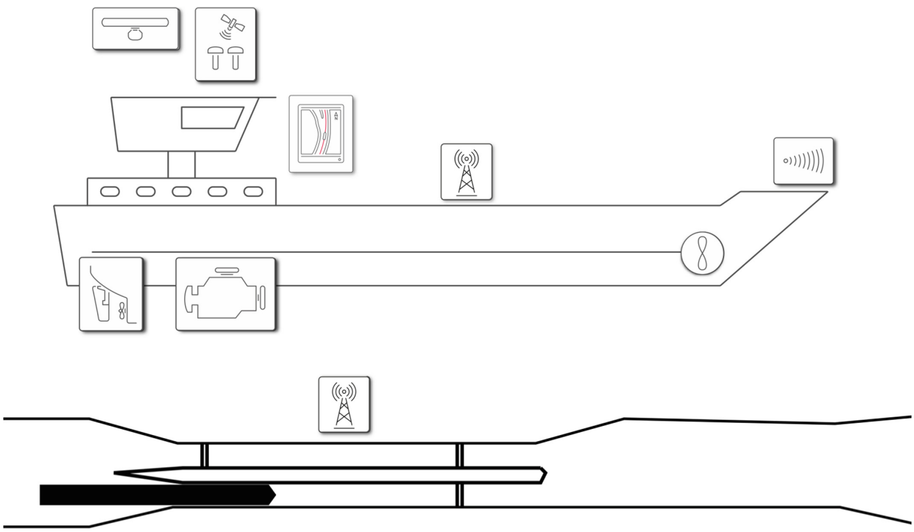


Fig. 1. Overview of SciPPPer system

2.1 Actuator Requirements

The employed control algorithm requires the independent setting of longitudinal and lateral forces as well as a moment about the vertical axis. This translates into a limitation of possible actuator configurations. Table 1 shows the configurations that fully satisfy the demand in green. Configurations that satisfy the constraint fully in theory but have limitations in the control performance due to other actuator constraints in yellow. As an example, vessels with one azimuth propeller in the front and a classical bow thruster fall into this category. This is because while this configuration may be able to apply forces in all directions, the rate of change of the forces is strictly limited by the turning speed of the azimuth thruster. Applying a forward force after applying a force backwards clearly illustrates this drawback. This limits the control performance dramatically and should be avoided. Configurations that are not taken into account are marked red. Apart from this, the continuous control of all actuators is preferred.

Table 1. Actuator configurations

Actuator Bow / **Actuator Stern**	No Actuator at Bow	Classical Bow Thruster (90° oder - 90°)	360° Thruster	Bow Rudder
1x Propeller Fixed with Rudder				
2x Propellers Fixed with Rudder				
1x Propeller Fixed with Rudder and Flanking Rudder				
2x Propellers Fixed with Rudder and Flanking Rudder				
1x 360° Propeller (Azimuth)				
2x 360° Propellers (Azimuth)			Simulator Trials	
3x 360° Propellers (Azimuth)		Full-Scale Trials		
4x 360° Propellers (Azimuth)				

2.2 Position and Orientation Measurement Requirements

Typical locks on European waterways have a width of 12 m. The ship that are built to pass these locks are 11.45 m wide. This results in a lateral margin of less than 30 cm. The ships' lengths vary between 80 and 180 m. In order to be able to enter a lock automatically, the positioning accuracy as well as the control performance need to be well below 30 cm in lateral direction. Table 2 shows the requirements for the positioning and orientation accuracies for the different phases and different sensor systems. Note that phases 2, 3, and 4 are the most critical. GNSS may not be reliable during these phases due to low satellite visibility because of high lock walls. Accuracy is specified as 95% (2σ) of all measurement values being within the interval $\pm 2\sigma$ around the true value, σ being the standard deviation.

Table 2. Accuracy requirements for sensor systems

Phase	1	2	3	4	5
Positioning accuracy bow lateral GNSS [cm]	10	-	-	10	10
Positioning accuracy stern lateral GNSS [cm]	10	10	-	-	10
Positioning accuracy longitudinal GNSS [cm]	10	10	10	10	10
Resulting orientation accuracy [°] (cm) for ship length L=100m	0.11 (20)	0.11 (20)	-	-	0.11 (20)
Longitudinal speed GNSS [cm/s]	10	10	-	-	10
Lateral speed GNSS [cm/s]	1	1	-	-	1
Time to alarm PNT unit [s]	10 (position) 2 (heading)	10 (position) 2 (heading)	10 (position) 2 (heading)	10 (position) 2 (heading)	10 (position) 2 (heading)
Positioning accuracy bow lateral Lidar [cm]	-	1	1	1	-
Positioning accuracy bow longitudinal Lidar [cm]	-	-	10	-	-
Positioning accuracy stern lateral Lidar [cm]	-	-	1	1	-
Resulting orientation accuracy [°] (cm) for ship length L=100m	-	-	0,005 (1)	0,005 (1)	-
Longitudinal speed Lidar [cm/s]	-	-	1	-	-
Lateral speed Lidar [cm/s]	-	1	1	1	-
Time to alarm Lidar [s]	1s	1s	1s	1s	1s

2.3 Control Performance Requirements

The overall deviation consists of errors from position and orientation estimation as well as deviations from automatic control. Table 3 shows the accuracy requirements for the control performance for the lock passage phases 1–5. They are determined together with requirements for the pose determination task such that there is an extra margin for error of 10 cm for bow and stern for a ship of 100 m.

Table 3. Accuracy requirements for control systems

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Control deviation longitudinal position y [cm]	Not relevant	Not relevant	100	Not relevant	200
Control deviation lateral position x [cm]	50	10 (bow) 20 (stern)	10	20 (bow) 10 (stern)	50
Control deviation orientation [°] (cm for ship length L = 100)	0.23 (40)	0.11 (20)	0.057 (10)	0.11 (20)	0.23 (40)
Control deviation ROT [°/min]	2	2	2	2	2
Control deviation speed [cm/s]	10	10	10	10	10

3 Control System

The control system consists of several modules that are shown in Fig. 2. The sensor data is fed into a state estimator in the form of an extended Kalman filter. Once the final position within the lock has been chosen by the skipper the planning module plans a transition trajectory for the position and orientation as well as corresponding speeds from the initial state to the destination. This desired trajectory minus the current state from the Kalman filter forms the control error and is fed into a multi-input multi-output controller. The controller calculates forces in x and y as well as a moment about the vertical axis. This values are added to a values from a feedforward block which calculates nominal forces in x and y as well as a nominal moment using an inverted mathematical model of the vessel. A classical thrust allocation block computes RPMs and angles for the involved actuators. These signals are fed into the propulsion control system.

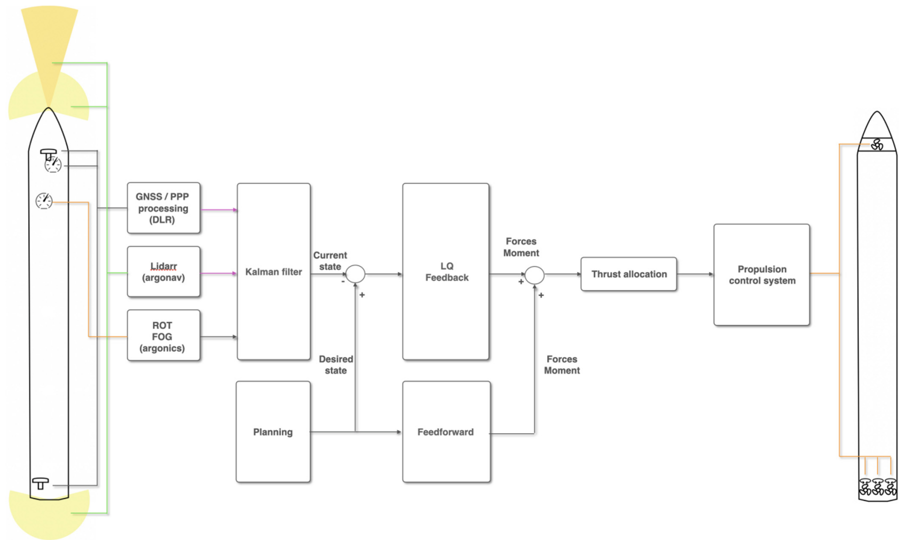


Fig. 2. Control system modules

3.1 Kalman Filter

The state estimator is implemented as an extended Kalman filter with the following dynamical states: N/S position, E/W position, N/S velocity, E/W velocity, with respect the center of gravity of the vessel as well as heading and rate of turn about the vertical axis. Thus, a classical 3DOF (degrees of freedom) model is used neglecting heave, pitch and roll. The inputs are three positive thruster RPMs as well as thruster angles in the case of 2 azimuth thrusters in the back and one in the front. In the case of a classical bow thruster, the third angle is fixed at 90° with the respective thruster RPM being positive and negative. Since the differential equations ask for forces and moments the actuator variables are transform using the inverse thrust allocation module.

3.2 Planning

The planning calculates desired values for all dynamical states. This is carried out in several phases: Phase 1 starts with the current state as initial value and plans a trajectory to a position in front of the lock with the middle of the ship being aligned with the middle of the lock chamber and the orientation being the orientation of the lock chamber. The respective speeds form at the desired position and orientation pose a design choice. The second phase starts with the last state of phase 1 as initial value and the desired position and orientation in the lock chamber as final state. Cubic splines in the velocity states ensure smooth transitions between the different poses.

3.3 Controller

The controller follows a two degree of freedom control strategy in the form of a feedforward as well as a feedback module. The feedforward module uses an inverted dynamical model which allows for the computation of nominal forces and moments from the desired trajectory. The employed mathematical model is not able to describe the dynamics perfectly, unmodeled disturbances also contribute to deviations when applying these nominal forces and moments. In order to compensate for these deviations, a feedback controller is implemented. This Riccati-type controller uses a static gain matrix and is therefore an infinite horizon linear quadratic optimal controller which is not taking constraints into account.

4 Results

This controller setup has been tested on the full-bridge simulator at Bundesanstalt für Wasserbau (BAW) in Karlsruhe on a cruise ship with 2 azimuth thrusters at the stern and one azimuth thruster at the bow during several simulation runs. The results of these simulator tests can be requested from the authors. Numerous simulator runs involving different types of actuator configurations have been performed at Argonics in Stuttgart at the in-house simulator station using a similar mathematical model as the one at BAW.

The first full-scale trials were carried out on the sister ship to the one in Karlsruhe at Hollands Diep. The final results were demonstrated again on a cruise ship which has three thrusters at the stern and a classical left/right bow thruster. This bow thruster was not continuously actuated but only offered four distinct RPM settings. This was compensated for by a special actuation strategy in order to not have to take the switching property into account explicitly. However, this limited actuation resulted in lower control performance.

Figures 3, 4, 5 show the desired values as well as the actual values for the lateral position, heading as well as longitudinal speed. At 12:30 h the lateral position jumps significantly. This is due to the stern Lidar sending faulty measurements. The state estimator weighs the different inputs but is unable to fully compensate for this error.

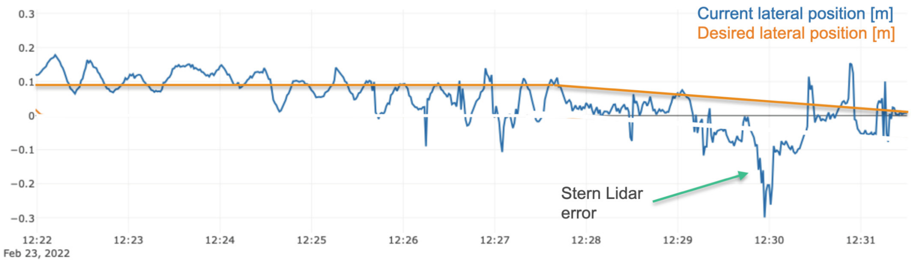


Fig. 3. Desired and estimated lateral positions

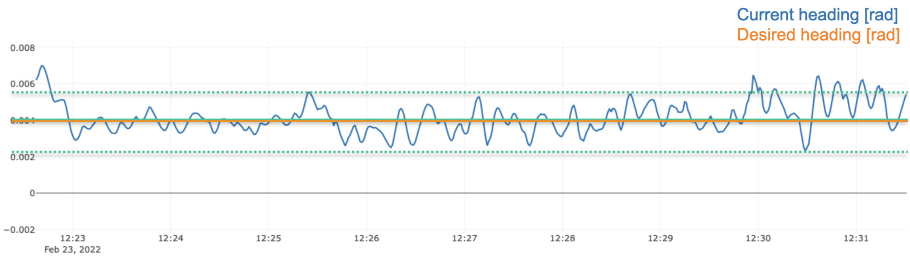


Fig. 4. Desired and estimated heading

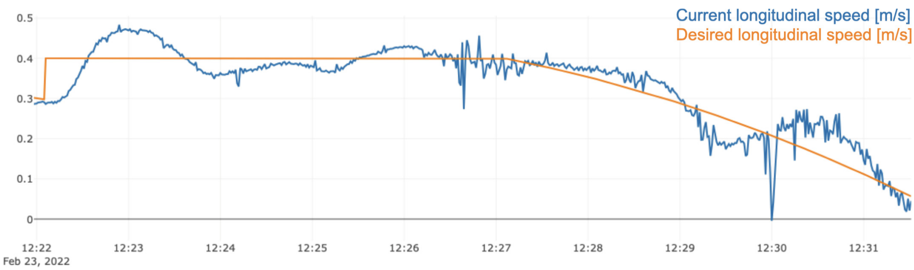


Fig. 5. Desired and estimated longitudinal speed

Table 4 shows the requirements next to the results of a typical trial run. The longitudinal position was not controlled very firmly due to the fact that the length of the lock basin was far greater than the ship length. Unfortunately, the tight requirements could not be met fully. This is mostly due to the fact that the bow thruster had the above mentioned switching property with only 4 distinct RPM settings as opposed to the required continuous operation. However, adding up the different errors laterally the total error adds up to 26 cm which is still below the overall requirement of a maximum of 30 cm.

Table 4. Requirements and achieved values

Control deviation	Requirements	Full-scale trial (Offset compensation)
Longitudinal position y [cm]	100	<250
Rate of turn [°/min]	2	2.23
Orientation [°]	5,73/L	
° at ship length L = 85m	0.06	0.11
cm at ship length L = 85m	10	16
Lateral position x [cm]	10	<10
Velocity [cm/s]	10	10

5 Conclusions

The research project SciPPPer was able to show that it is possible to automatically pass a lock with existing inland vessels using additional close proximity sensors such as Lidar as well as centimeter-grade GNSS receivers. PPP corrections distributed via VDES in broadcast mode showed to be a promising option for future high-precision GNSS services around existing infrastructure. The extremely tight constraints when passing a lock require serious calibration of all sensors. Small errors can already lead to a violation of these constraints. The automotive radar sensors were not precise enough to serve as a backup for the Lidar measurements. Error detection within the estimation algorithm still needs some further refinement. The control setup was able to achieve the requirements in the simulation runs even under undesirable environmental conditions. However, the desired requirements were not fully met during the full-scale trials due to the switching behavior of the bow thruster. However, several completely automatic runs were carried out successfully without intervention by the skipper. The control system stayed within the total bounds set by the difference of the lock basin width minus the width of a typical vessel.

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