Impact of a navigation aid on unmanned sailing in inland waterways: Design and evaluation challenges

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Abstract—The Hull to Hull project is initiated within the Horizon 2020 programme of the European Union to assist mariners and support safe navigation while increasing the level of autonomy. As it is important to validate the resilience and integrity of such systems, the authors aim to measure the impact of this navigation aid in Inland Waterways. This task is not straightforward as there is no clear framework for applicable performance metrics. Additionally, inland vessels require more accurate positioning and higher situational awareness as they usually operate in constrained waters and the proximity of other vessels. Furthermore, operating an unmanned vessel produces additional challenges as there is no crew on board. Therefore, this paper discusses the design challenges in implementing this navigation aid to an unmanned vessel in inland waterways and also proposes an approach for evaluating its impact with domain-specific performance metrics and criteria. The outcome of this study sets the foundation for future validation.

Index Terms—inland navigation, unmanned sailing, shore control, performance metrics

I. INTRODUCTION

One of the most important factors in the transition to autonomous surface vessels is having robust navigation systems. As a step towards this target, a consortium of European research institutes has begun to work on the Hull-to-Hull (H2H) project to aid the ship handlers in navigational decisions. The H2H concept builds upon using uncertainty zones to visualize the relative positioning between vessels and objects using H2H engines and applications [2]. Making use of the European Global Navigation Satellite Systems (GNSS) Galileo/EGNOS, and fusing data from different sensors along with 2D/3D models, this system will allow vessels to sail in close proximity to each other and other objects present in its maritime environment [1].

The H2H system supports a rich variety of vessels. However, unlike seagoing vessels, inland vessels have spatial limitations and this leads to more precise localization requirements. Therefore, the authors are mainly concerned with the evaluation of H2H navigation in inland waterways (IWW). This

paper discusses the design and evaluation challenges in this effort, and approaches how to tackle them. To validate the resilience and integrity of H2H navigation, the authors suggested 3 test scenarios which are the most common use cases in IWW: (i) general sailing, (ii) docking, and (iii) lock passing. These validation scenarios will be eventually tested on a 1/8 scale model of a CEMT-1 (Conférence européenne des ministres des Transports) vessel class, shown in Fig. 1. However, there are two main challenges in the envisaged evaluation procedure. First, because this research vessel is designed to eventually sail autonomously, there is no space for a skipper on board and this adds further communication demands for remote control. Second, there is no known satisfactory metric to measure quantitatively and precisely how a skipper performs with and without an aid like the H2H system. To address these challenges, two questions were handled: (i) How to extend the present remote control options with a full-featured design for the H2H project?, and (ii) How to measure the impact of a navigation aid such as the H2H system?

Fig. 1. Scale Model Barge - Cogge.

This paper continues as follows: first, section 2 briefly explains the H2H concept, section 3 depicts the components

of the research vessel to be used in the experiments, section 4 discusses the design challenges for the H2H system implementation and solutions, section 5 explains the evaluation method along with the performance metrics and lastly, section 6 concludes our approach and suggests the future work for experimental validation.

II. H2H CONCEPT

The core functionality of the H2H system is to provide the hull-to-hull distance between H2H moving objects (vessels) or H2H stationary objects (e.g. dock), and to use the concept of uncertainty zones to visualize the uncertainty of the positioning/distance calculations. Based on the dynamics of the ship and current operating scenario, the uncertainty zones change shape and size (Fig. 2), and different notifications are presented to the operator based on the overlapping of the uncertainty zones [3]. To calculate the hull to hull distance, it is required to know the location of the hull relative to the other hull/object and communicate this information between H2H objects. This is achieved by using positioning and movement sensors, the 2D/3D models of the vessel(s)/object, the H2H engines, a communication channel between the H2H objects, and the H2H applications (user interface/software). For the sake of simplicity, we will refer to all these components with the term “H2H system”. The details of the H2H system are explained in [2].

Fig. 2. Representation of dynamic uncertainty zones while docking [3].

III. EQUIPMENT

As an attempt to bridge the gap between the growth of inland cargo transport and the outflow of small inland vessels, Watertruck+ project was initiated to increase the flexibility in waterborne transport by introducing a modular fleet of both barges and push boats [4]. Given the growing research interest in inland shipping, the IMP research group of the KU Leuven has designed and built a 1/8 scale model of a Self-Propelled CEMT-I (SP-CEMT I) Watertruck+ vessel named Cogge, which has an over-actuated propulsion system enveloping a

360-degrees-steerable bow thruster in combination with a 360-degrees-steerable 4-channel stern thruster [6].

In the current design of Cogge and its operation, three main subsystems form the overarching hardware and subsequent communication architecture: an actuation control subsystem, a sensor and autonomy subsystem, and a shoreside subsystem. Fig. 3 illustrates their vital inter- and intra-communication links.

IV. DESIGN CHALLENGES

The main challenge of the H2H system evaluation in terms of design is the reliability and flexibility of the full-featured system and corresponding communication layer. Fig. 4 presents the general scheme of the H2H concept between a vessel and another vessel or landmark. However, a modified configuration has to be designed for IWW experiments with the Cogge, due to its unmanned nature and limited space for additional equipment. In this modified configuration which is presented in Fig. 7, the H2H engine and related components have to be transferred to the shore side and combined with the shore H2H object. Moreover, as we need an application to aid the skipper, the H2H application for visualization has to be realized at the Shore Control Station (SCS) of the vessel, which dictates another communication channel. Therefore, there are 3 sites to be considered for the H2H project experiments in the IWW: (i) the vessel (H2H moving object), (ii) the shore site that will contain the shore components of the H2H system, i.e. dock/lock (H2H stationary object), and (iii) SCS of the vessel that is foreseen to be stationary at one of the KU Leuven offices.

As such, after modifying the configuration of the H2H system, the primary needs for our study are (i) streaming quality live videos, and (ii) remote controlling. Additionally, low latency and failover solutions are also critical for safe operation. To better understand the demands of the H2H experiments, we will first discuss our communication approach and then explain the extensions/additions at each site.

A. Communication

The pilot version of the H2H system uses Maritime Broadband Radio (MBR) as the communication means between two H2H objects. MBR is a line-of-sight RF communication technology designed for maritime use [7]. However, due to the abovementioned requirements and distance between the vessel and SCS, we decided to establish dedicated channels for Camera-SCS and PLC (onboard)-PLC (SCS) communications over 3G/4G, instead of using the current configuration or MBR. This will avoid the possible delays and ensure a continuous HSI link between the vessel and the SCS. While these two are related to better remote controlling the vessel, a vessel-shore (MBR) and a shore-SCS (4G) channel need to be established too in order to add the H2H navigation functionality to our design. Fig. 5 presents the needed communication channels for the smooth operation of the vessel while using the H2H system.

Fig. 3. Inter- and intra-communication links of the different hardware subsystems [6].

Fig. 4. General H2H Concept.

Fig. 5. Representation of the communication channels among 3 sites.

B. Extension to Sensor and Autonomy Subsystem

For this study, onboard sensors/devices are extended for two reasons: (i) to simulate the view of the skipper, and (ii) to transmit the navigation states (i.e. position, speed, orientation) to the shore. This extension includes 3 Internet Protocol (IP) cameras to visualize the front, starboard and port view that a skipper would see, a POE switch to forward data coming from cameras and the GNSS receiver, a 4G router to stream live videos, and an MBR antenna to transmit navigation states to the shore site. To further simulate a realistic view, considering the scale effect, all cameras are placed 22.5cm higher than the top plate of the vessel, which is the scaled height of a 1.80cm skipper.

To display smooth live videos at the SCS, onboard cameras have to be able to reduce the data throughput by adjusting several parameters such as the resolution and frames per second (fps) without dramatically reducing the image quality. Therefore, configurable IP cameras have been chosen. We require to stream 720p videos to SCS at 24fps with low latency (0.2sec). During the offline tests with this configuration, the data demand of one camera was 2.5 Mbps on average with peaks up to 5Mbps. Given the average upload speed (11 Mbps) of the Belgium mobile network market [8], a 4G router with two modems has been chosen. As live streaming the camera feeds to the shore is the most demanding data application, this router also has bandwidth combining, failover, and redundant SIM card slot features to stream a smooth live view from 3 cameras.

C. Shore Control Station

As shown in Fig. 3, the actuation control subsystem of the vessel houses a second level of modularity induced by the nested PLC topology. This PLC controls the lowest

level desired actuation system states, and these states can be communicated to the PLC from shoreside via the shoreside subsystem. Currently, this subsystem includes a remote control that uses a radio link, and (ii) a shoreside laptop that uses mobile or wireless internet. The details of these subsystems are explained in [5].

However, for H2H experiments, the shoreside subsystem is turned into a full-featured SCS (Fig 6) prioritizing the Human-System Integration. This SCS includes a powerful computer, a control box, multiple curved displays for realistic visualization and H2H application monitoring, and a router for a pier-to-pier (P2P) Virtual Private Network (VPN) connection with the cameras of the vessel over the 4G mobile network.

The current remote control over radio link replaced by an improved conning box. It is designed with the same Azimuth Controllers for the bow and stern thrusters as the full-scale Watertruck+ barge and a Human-Machine Interface (HMI) connected to a PLC which communicates with the onboard PLC over a dedicated 3G VPN. During initial tests, the average latency between the command given on the control box and the command received onboard Cogge was 0.2 seconds.

Fig. 6. Shore Control Station representation of the Cogge.

Situational awareness is ensured by displaying the forward, port and starboard camera feeds from the vessel on 3 curved screens, showing the H2H application (visualization) on one display, and presenting the control indicators (i.e. course, speed, heading) on the HMI of the conning box.

D. Shore Components

As discussed above, the unmanned nature of the vessel implies that some parts of the H2H equipment need to be moved from the vessel to the shore side. The modified H2H system for IWW is shown in Fig. 7. The shore side components include the combined H2H engine for both the moving and stationary H2H objects, the Dynamic Positioning System (DPS) units for differential positioning between two H2H objects, and an MBR antenna for receiving navigation states. In this modified configuration, the navigation states of the vessel are sent from the vessel to the shore over MBR,

and all other data is processed on the shore side. The DPS units combine the localization data of the shore landmark and the vessel, and feed the H2H engine. Then, the H2H engine locates the 2D/3D model of the vessel relative to the shore landmark (e.g. dock) model.

Fig. 7. Modified H2H System for IWW.

As seen from Fig. 7, the H2H application is realized at the SCS using the data coming from the H2H engine. Thus, a 4G router is also installed on the shore site for communication with SCS over the 4G network to provide the H2H application at SCS with the H2H engine data.

V. EVALUATION CHALLENGES

In addition to the design aspect, evaluating the efficiency of the H2H navigation is challenging because there is no known satisfactory metric to measure quantitatively and precisely how a skipper performs with and without an aid like the H2H system. Thus, we first need to define the performance metrics to measure. Then, we will discuss our method and the details of the experiments for analysis.

A. Performance Metrics

Performance evaluation is a difficult task. Although there are studies that describe performance metrics for products or systems, there is no broadly accepted approach as most of them suffer from limitations such as lack of a comprehensive system level approach [10]. A relevant evaluation approach for our study is proposed by Messina [11] that provides a general framework and a set of guidelines to facilitate performance measurement of unmanned systems.

Additionally, to clarify quotes such as “increased performance”, two commonly used dimensions of performance are defined as (i) efficiency and (ii) effectiveness [9]. While effectiveness refers to the level of requirement fulfillment, efficiency measures the available resource consumption. Following the guidelines described in [11] and staying in these two

dimensions, we defined 5 metrics for our impact evaluation approach and explained our motivation to choose them.

1) *Time efficiency*: In many applications, measuring the time spent is one of the most widely used efficiency metric to understand operational performance. We will measure the time spent to complete each test run.

2) *Energy efficiency*: In addition to its operational aspect, energy consumption is also widely used nowadays to present the sustainability of a product or a system. Similar to the time efficiency, it is important to understand how much resource is consumed to complete a task and we will compute this value taking into account the wind resistance to make a fair comparison between each test run.

3) *Accuracy*: For every mission, there is a desired state and the goal is to perform as close as possible to that state. For the straight sailing scenario this end state is to execute the planned path. Therefore the accuracy metric is defined as the cross-track error which we will calculate as the Root Mean Square Error (RMSE) of the executed path.

For docking, on the other hand, the desired state is to bring the vessel alongside the quay/dock so that the vessel can be docked smoothly with the help of deck activity (e.g. ropes). It is worth noting that the goal is not to drive the vessel directly alongside the dock. Rather, the goal is to put the vessel in a position that is parallel to the dock with a clearance equal to the width of the vessel. Therefore, the accuracy in the docking mission translates into how accurate this final pose is. We will calculate this metric as the RMSE of the fore and aft GNSS antenna positions with respect to their desired positions.

This is an effectiveness metric and the requirement for all missions is to have an RMSE below 1m.

4) *Safety*: The main goal of the navigational safety is to avoid collisions while executing the given task and if a system improves the safety, that is an important indicator. For this study, the safety metric is described as how close a vessel is to a collision with static objects. Therefore, we will measure the safety as the closest point of approach (CPA) of the hull of the vessel to the static obstacles and the dock using the position, orientation, and vessel geometry. As this is an effectiveness metric, the requirements are not to sail closer than 0.5m to the shore or the static obstacles while sailing, and not to touch the dock while docking.

5) *Reliability*: Reliability is an overall effectiveness metric. It is also important to know that if the task is completed within the given requirements to present how reliable a system is. For our experiments, the success of each mission will be specified as a binary variable considering the requirements for accuracy and safety metrics in Table I as the success criteria. Then, the reliability of the system will be discussed according to the overall results.

B. Method

As stated before, this study aims to set the foundation to conduct experiments for straight sailing, docking, and lock passing in IWW. The authors have chosen the Leuven-Dijle Canal as the test area due to its suitability to test all three use

TABLE I
PERFORMANCE METRICS AND REQUIREMENTS

Metric	Dimension	Requirements
Time	Efficiency	-
Energy	Efficiency	-
Accuracy	Effectiveness	$RMSE_{sailing} < 1m$, $RMSE_{docking} < 1m$
Safety	Effectiveness	$CPA_{sailing} > 0.5m$, $CPA_{docking} > 0$
Reliability	Effectiveness	Successful mission

case scenarios. For each use case, a mission with details such as the desired waypoints/final position, start/end indicators, and the positions of the static obstacles will be defined. The lock passing scenario will be treated as a combination of sailing and docking missions. Then, a group of users will be asked to perform these missions under two configurations: with and without the H2H system (independent variable). As the target audience is certainly from the maritime domain, conducting experiments with only skippers would be preferred. However, considering the available sample size for testing, the authors decided to invite a group of students to the experiments. The motivation is that this addition may improve the quality of analysis by splitting the user group variable into two control variables representing “domain knowledge” and “gaming/remote control experience”. Because it will increase the power of statistical effect by increasing the size and it will allow us to derive subtle conclusions that may stay hidden otherwise.

Fig 8 presents our analysis approach. For evaluation, the performance metrics (dependent variables) of the test runs without the H2H system will establish the reference criteria for each user and the impact of the H2H system will be quantified by benchmarking the performance metrics against these reference values. Then, the results will be discussed for each use case, taking into account the domain knowledge and the control experience of the users.

Fig. 8. Analysis approach.

VI. CONCLUSION AND FUTURE WORK

This paper described the challenges and proposed solutions to present the impact of the H2H system in IWW navigation. It is argued that due to the unmanned characteristic of the vessel, the overall configuration of the H2H system components needs to be modified and this adds additional communication needs. Then, the modifications and modular extensions to overcome this challenge are explained.

It is also argued that, in addition to the design aspect, evaluating the efficiency of the H2H system for single-handed sailing requires a new approach as generic frameworks do not apply to this unique study, and a statistical method along with five performance metrics is proposed.

At this stage, the hardware modifications/extensions to the vessel and shore modules are already applied. The latency of the commands and the camera feeds is 0.2sec which validates our solutions to the explained design challenges and sets the stage for live experiments. This study will continue with conducting the water tests and applying the proposed evaluation method to the analysis. The authors plan to carry out this work at the Leuven/Dijle Canal during the summer and discuss the results in future work.

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