Use of Uncertainty Zones for Vessel Operation in Inland Waterways

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Abstract: European inland waterways represent an underutilised avenue of transport. Increased use of this avenue has the possibility to decrease emissions and remove traffic from congested roadways. However, there is a shortage of skilled shippers and labour costs threaten to make waterway transport economically unviable. By creating smart ships, the requirement for skilled shippers decreases. The Hull-to-Hull (H2H) project, part of the European Horizon 2020 program, aims to do this through various methods, one of which is the creation of a smart ship navigation system. This system makes use of uncertainty zones in its display and control software to assist a vessel’s helmsman in making safe navigation decisions. Based on the ship’s dynamics and current operating scenario, the uncertainty zones will change shape and size, and different notifications will be given to the helmsman based on the overlapping of the uncertainty zones. This paper focusses on the uncertainty zone based navigation system currently being developed for the inland waterway use case.

1. Introduction
The inland waterway network in Europe presents a significantly underutilised opportunity for cargo transportation. Increased usage of this opportunity will decrease congestion on motorways and railways, expand cargo transport capacity and be more environmentally friendly than land or air based cargo transport. The European commission aims to shift 30% of road freight transport in 2011 to either railway or waterborne transport, and at least 50% by 2050. [1] However, a major obstacle to this idea is the lack of skilled sailors. A future solution to this problem is the implementation of unmanned ships, but technology has not yet advanced far enough to safely and economically implement this. In the meantime, an intelligent ship navigation system could enable safe single handed sailing, resulting in decreased labour costs and increased safety. It can also be used as a stepping stone towards autonomous shipping.

1.1. The Hull-to-Hull System
As part of the Horizon 2020 program, a consortium of European research institutes have begun work on the Hull-to-Hull (H2H) system. This system will allow vessels to sail in close proximity to each other and other objects present in the maritime environment. The system makes use of the European Global Navigation Satellite System (EGNSS), European Geostationary Overlay Service (EGNOS) and
Galileo to help mariners make safe navigation decisions, even while in close proximity to other objects, by providing accurate positions of vessels and objects in the surrounding area. Other objects can mean docks, locks, or obstacles to be avoided. This system aims to enable safer maritime navigation decision making in comparison with current navigation systems and decrease the amount of crew required onboard vessels.

The formal objectives of the Hull-to-Hull system can be found at [2]. There are five partners in the consortium, namely Kongsberg Seatex, Sintef Ocean, Sintef Digital (all Norway), Mampaey Offshore Industries (Netherlands) and KU Leuven (Belgium). KU Leuven is responsible for the inland waterways implementation of the H2H system.

In the inland waterways implementation, there are three possible operational scenarios that will be considered:

- General sailing
- Docking
- Lock passing.

Each of these scenarios and how uncertainty zones (UZ) are used for them will be explained in further detail later on in the paper.

1.2. H2H Sensors and Data

The H2H system makes use of modern sensors to achieve its required accuracy. As previously mentioned, GNSS is used for location. The GNSS system to be used is the Septentrio AsterRx-U Marine, which has an RTK performance in ideal conditions of 0.6cm horizontal and 1cm vertical accuracy. Additional sensors are also used to increase position accuracy, such as a Light Detection and Ranging device (LiDAR) and an Inertial Navigation System (INS). The LiDAR will be used to percept objects, and as a secondary localisation sensor to complement the GNSS system. The LiDAR that will be used is the Neptec OPAL-1000 for the inland waterways use case. The INS will also be used as an additional sensor for localisation, to be fused with the GNSS data. The INS to be used is the Ekinox-E INS. These three sensors are shown in Figure 1. Vessels will also exchange relevant data, such as position, course, speed and ship data over Ultra-Wideband (UWB) in the H2H system, thereby increasing the amount of information available to each vessel which can then be used to plot relevant data on the H2H interface.

![Figure 1: GNSS, LiDAR and INS for Inland Waterway Use Case](image)

Another part of the H2H system is that the CAD models of vessels are shared when they come into proximity with each other. This enables the H2H system to determine how close vessels can approach each other before the proximity becomes hazardous, based on the vessels’ shape and size.
2. Uncertainty Zones

This paper discusses the visualisation of the H2H system, focusing on the UZs developed for the inland waterway use case. All vessels and objects of interest will be assigned a UZ. The definition of an UZ is a multi-band zone around a vessel or object of interest. In the case of vessels, the size of the UZs are determined by size of the vessel (CAD model), its manoeuvrability and current speed and heading. Current speed and heading information will be calculated from the GNSS and IMU data. The size of an object’s UZ is calculated by using the size of the object itself. Objects of interest will be objects which should be avoided, such as bridges, locks, docks and obstacles. When the UZs overlap, warnings will be given to the helmsman, as well as a suggested course of action. These warnings will progressively become more urgent, depending on what level of UZ overlapping has occurred. The UZs will be dynamic, and change shape based on the vessel’s velocity and heading. While the concept of UZs remains the same, different situational scenarios have their own suggested courses of action depending on which zones overlap.

The H2H UZ system is similar in some ways to the ship domain system [3][10]. However, in this case there is more than one UZ, and the zones change dynamically based on the vessels course and velocity. The UZ shape is also based on a CAD model of the vessel.

The ship domain system was further improved in [4]. Here, an algorithm is used in combination with ship domain to calculate the last point in time when a ship is able to avoid collision with another ship. The implementation of a similar algorithm would be useful in the H2H concept, in determining a course of action to avoid collision, and when collision is perceived to be inevitable. The idea of using advanced sensors installed on ships would also increase the accuracy of the avoidance calculation algorithms. Methods of calculating ship domain and mathematical descriptions thereof were also presented in [5].

Using algorithms to solve collision problems is used in [6], where the authors present a danger avoidance algorithm. This algorithm was shown to work under simulation conditions. Multisensory fusion, in the form of using multiple radars, was also used in [7]. Here, data from multiple radar is used to compute the distance to closest point of approach, and collision risk is calculated using Dempster-Schafer theory. Another approach presented in [8], detects collision candidates based on the perspective which considers a ship encounter as a process, rather than analyzing traffic data at certain time slices. At present, AIS data is being primarily used for collision detection [9]. However, H2H system will open for real-time information sharing with comprehensive information for more precise detection algorithms. This is applicable to H2H in that an end goal would be to combine data from multiple sensors based on different vessels.

The concept of uncertainty zones in the form of ship domains is not a new concept [10]. However, most literature is focused on collision avoidance, whereas in H2H, in the case of docking and lock passing, a controlled collision is the actual goal. The H2H system will undoubtedly draw upon previous research, adapt it, and seek to test and implement these concepts and algorithms in a real-world solutions.

Figure 2 shows an approximate representation what the helmsman will see of the H2H system. The H2H data will be presented to the helmsman on an electronic screen. This can be used in conjunction with other displays present in the cockpit, such as Automatic Identification System (AIS) display and radar screen.
2.1. Uncertainty Zone Definitions

Table 1 shows the basic colour conventions used in the H2H concept, and actions to be taken if the zone is infringed upon. There are three types of zones, each with a specific course of action based on the current scenario (general sailing, docking, lock passing). Normally, there will be three UZs: green, yellow and red. When a green zone intersects with another H2H object’s UZ, a preliminary warning will sound. An H2H object is regarded as an object such as a vessel, lock, or dock which is fitted with the H2H system. Should the yellow zone intersect with another object’s UZ, a more urgent warning will sound. If a red zone is intersected, an alarm is sounded, as the system will assume that a collision is imminent. However, in the case of docking and lock passing, the objective is for the red zone to be intersected, therefore in that scenario the system will notify the helmsman that the vessel is in the docking position and ready to be secured to shore.

Table 1: Uncertainty Zone Definitions

| Uncertainty Zone | Description | Colour Convention |
|------------------|-------------|-------------------|
| Tracking Zone    | Start tracking if anything comes in the proximity of the tracking zone. | ![Green Zone](image) |
| Intermediate Zone| Start suggesting evasive maneuvers and generate audible warnings. | ![Yellow Zone](image) |
| Collision Zone   | Contact is assumed. | ![Red Zone](image) |
Figure 3 shows change in the size of UZs based on a vessel’s dynamics. In the low inertia diagram, the vessel is moving slowly, and/or has a low mass. The result of this is that it would be able to stop or change direction in a relatively short distance. If the vessel increases its velocity and/or mass, thereby increasing its inertia, the UZs increase in size, because there is now a larger area to take into account should the vessel need to stop or change direction.

Figure 3: Dynamic uncertainty zone for different vessel dynamics

Figure 4 shows what the helmsman would see on the graphical interface of the H2H system. The visualisation will also include waypoints the vessel should follow to reach its destination (WP in Figure 4). Objects which are not fitted with the H2H system, such as the vessel labeled “AIS PZ” which is fitted with an AIS transponder, will still be assigned UZs by the H2H system but they will not be as detailed as the other H2H objects, since it is only be possible for H2H devices to share the required information to enable the creation of accurate UZs.

Figure 4: General sailing graphical interface with example H2H objects

2.2. General Sailing
General sailing is considered to be when a vessel is sailing along a planned route in an inland waterway. It does this by following predetermined waypoints, which can be seen in Figure 5. Should
another object be detected, such as the case in Figure 6 where another H2H vessel has been detected, the H2H system can modify the waypoints to avoid a collision or a hazardous close proximity situation. To do this, the H2H system takes into account both systems’ waypoints and dynamics, to calculate alternative waypoints for the vessels to follow. In the Figure 6, alternative waypoints, labelled as EWPs, for Evasive Waypoints, have been calculated for Vessel A, since it has been calculated that Vessel B would otherwise enter Vessel A’s UZ and vice versa.

Figure 5: General sailing with waypoints

Figure 6: Sailing with H2H object detected

In case of general sailing, the UZs interact with each other in the following ways, as presented in the table below.

| Warnings H2H Module | PZ Intersection | PZ Situation |
|---------------------|-----------------|--------------|
| 1) No warning.      | None            |              |

In case of general sailing, the UZs interact with each other in the following ways, as presented in the table below.

| Warnings H2H Module | PZ Intersection | PZ Situation |
|---------------------|-----------------|--------------|
| 1) No warning.      | None            |              |
2) Start tracking the object in the green zone.  Green-Green

3) Raise level 1 warning and suggest evasive maneuver.  Green-Orange

4) Raise level 2 warning for collision if no action is taken.  Orange-Orange

5) Raise level 3 warning for collision is imminent if no action taken by both vessels.  Orange-Red

6) Collision has occurred.  Red-Red

2.3. Docking and Lock Passing
While in the previous cases, the objective was to avoid the red UZs overlapping, thereby avoiding a collision. When it comes to docking, the objective is for the red UZs to overlap in a controlled collision. In this case, the dock is given a UZ as well, however there is only one zone (red) and it is static.

| Warning H2H | PZ Intersection | PZ Situation |
|-------------|-----------------|--------------|
| 1) No warning. | None | |
| 2) Velocity and heading suggestions for efficient docking. | Green-Red | |
3) Suggest gradual deceleration.

| Docking complete (Contact sequence) | Orange-Red |

2.4. Lock Passing
Similar conventions used in the docking procedure are used for lock passing. Like docking, the vessel needs to moor against the side of the lock while the water level is being changed. For this, it can follow the same procedure as that with docking. Figure 7 shows how the UZs will interact as the lock. As the vessel approaches the lock, it must first notify the lock operator that it is approaching. Assuming the required conditions are met, the lock will be opened. The vessel must then dock with the side of the lock, as shown in the right image in Figure 8. For this, it must follow the same procedure as the docking procedure. It is moored to the side until the water level has changed. Once this is complete, the vessel can undock and leave the lock, once the gates are opened.

![Figure 7: Lock Approach Procedure](image)

![Figure 8: Lock Docking and Departure](image)

3. Testing and Validation

3.1. Test Locations
The system must be tested and demonstrated in pilot scenarios before being introduced into commercial use. For the inland waterways scenarios, suitable test areas have been identified in the Vaart canal near to the city of Leuven. The Tildonk lock (Figure 9 and Figure 10) is where the tests
and demonstration will take place for the lock passing scenario. It is approximately 7.5 km downstream from the Vaartkom marina in Leuven.

![Figure 9: Tildonk Lock (Image taken from Google Maps)](image)

Figure 9: Tildonk Lock (Image taken from Google Maps)

The docking scenario will take place at a suitable pier on the Vaart canal. The preliminary chosen option is a pier which is approximately 2km from the Vaartkom marina in Leuven. Because the test vessel is smaller and lower than a full sized vessel, a pier which is suitable for smaller vessels must be used, such as the one in Figure 11.

![Figure 10: View of Tildonk Lock Gate](image)

Figure 10: View of Tildonk Lock Gate

![Figure 11: Dock on the Vaart (Image taken from Google Maps)](image)

Figure 11: Dock on the Vaart (Image taken from Google Maps)

For the general sailing scenario, testing will take place on the Vaart canal between the Vaartkom in Leuven and Tildonk lock.
3.2. Test Platform
The inland waterways pilot scenario will be tested on a 1/8 scale model of a CEMT-1 (Conférence européenne des ministres des Transports) vessel class, shown in Figure 12. This vessel is designed to eventually be fully autonomous, therefore there is no space for a helmsman on board. For the pilot tests, the vessel will be controlled remotely. A live stream using cameras mounted onboard will be used to simulate what the helmsman would see. The camera imagery and H2H visualisation will be presented to the helmsman on screens on either a following vessel or at a land based control station. The tests will then be used to determine how effective the H2H system is in enabling single handed sailing. Future work will be to implement and test the H2H system on a full-sized vessel.

3.3. Potential Risks and Mitigation
With the implementation of a new navigation system, there is always the likelihood that the operation thereof could go wrong during testing. As mentioned in the previous section, testing will take place on an unmanned vessel. During testing, the test vessel is always followed by a manned chase boat. Depending on the situation, safety lines are attached to the test vessel to prevent it from moving out of the designated area of operation, should there be a loss of control. The control architecture itself has many layers of redundancy. It is possible to control the test vessel through radio control remote, via Wi-Fi connection, or through web based control. There are multiple control platforms on-board, so should one platform fail, another can take over. Should the H2H system itself fail during testing, this can be promptly communicated to the personnel in the chase boat, who could then take over control of the vessel remotely.

Before the H2H system is made commercially available and installed on full-sized vessels, it will have to be rigorously tested to try remove all sources of error and failure. However, as has been seen with the implementation of new smart technology, it is impossible to account for every possible scenario, and errors may still occur when the system is used commercially. The H2H system is to be used in conjunction with an AIS system so should the H2H system fail, the ship’s operator could fall back onto using the AIS system for collision avoidance and navigation. AIS is obviously a far more mature technology than the H2H system, therefore it is less likely that this system will fail as well. Should the sensors on which the H2H system is based give conflicting data, the system can flag this and notify the operator. The operator can then decide on the best course of action, depending on the sailing scenario.

The H2H system is intended to be an aid to navigation of manned ships. It does not have any control of the vessel, therefore the final control decisions are always made by a human. Therefore, as a last resort, the human can steer the vessel visually should all navigation aids fail.

Figure 12: 1/8 scale model test platform
4. Conclusion
A uncertainty zone based smart ship navigation system has been proposed. Three scenarios have been proposed for the inland waterway version of the system, with planned operating procedures for the use of the uncertainty zones based on each stage of the scenarios. The system is in its design and development stage, with the demonstration to be ready by March 2020. It is planned that the H2H system will increase the safety of inland waterway shipping, while also decreasing labour costs by making safe sailing possible with less crew members on board than what is currently required.

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