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EXPERIMENTAL RESULTS ON COLLISION AVOIDANCE OF AUTONOMOUS SHIP MANOEUVRES

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ABSTRACT

In this paper, experimental results on collision avoidance of autonomous ship manoeuvres are discussed. The collision avoidance experiments are conducted on a navigation & control platform that has been presented in a mathematical formulation as well as in an experimental setup. The mathematical formulation of collision avoidance consists of three systems: vessel traffic monitoring and information system (VTMIS), collision avoidance system (CAS), and vessel control system (VCS). The experimental platform of collision avoidance consists of a physical system that has been used to generate experimental results. The experimental platform is further divided into two sections: vessel model and navigation & control platform. The vessel model consists of a scale ship, where the CAS is implemented. The navigation & control platform consists of hardware structure and software architecture that supported for vessel model navigation. Two ship collision situations are considered in this study, where one ship is implemented under the vessel model and another ship is simulated. Finally, the successful collision avoidance results with respect various collision situations are presented.

INTRODUCTION

Congested sea routes are enforcing ships to make close encounter manoeuvres. As such, safe navigation and ship handling procedures in maritime transportation have been enforced on those routes in recent years. Even though the navigators' trainings and experience could play an important role in safe navigation and ship handling, that could also have some limitations due to human and economical constrains. Furthermore, well trained and experienced navigators could be placed on the bridge most of the time to satisfy the operational and safety requirements (i.e. to avoid potential hazardous conditions of grounding, collision or near collision and, weather damaged). However, such an approach not be a realistic goal in ship navigation. As for the reported data, 75-96% of marine accidents and causalities are caused by some type of human errors [1], thus a well trained and experienced navigator can also take wrong navigation judgments, which can result in human casualties and environmental disasters.

To overcome these challenges in ship navigation, a concept called "e-Navigation" was presented by the International Maritime Organization (IMO) and the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) [2]. That consists of integrating modern maritime technologies, and implementing intelligent decision making capabilities to overcome the limitation of human subjective factors in ship navigation. Therefore, e-Navigation could eventually reduce navigators' sole responsibilities on ship navigation. Furthermore, a major portion of e-Navigation consists of collision detection and avoidance features and that is the major contribution in this study.

Therefore, a mathematical formulation for collision avoidance in ship navigation is proposed. It is expected that the proposed approach can reduce human subjective factors in ship navigation and that could eventually improve the safety in maritime transportation. The proposed mathematical formulation is implemented under an experimental setup that has further discussed in this paper. The experimental setup consists of a ship model and a navigation & control platform and that has been used to generate the results on collision avoidance of autonomous ship manoeuvres.

The structure of this paper is as follows: the second section contains the mathematical formulation of collision avoidance.

The third section contains an overview of the experimental setup that consists of a ship model and a navigation & control platform. An extensive discussion on the experimental results in ship collision avoidance is presented in the fourth section. Finally, the conclusions are drawn in the fifth section.

MATHEMATICAL FORMULATION

The mathematical formulation of collision avoidance consisting of intelligent guidance features in ship navigation is presented in Figure 1. Three main systems/modules are available: vessel traffic monitoring & information system (VTMIS), collision avoidance system (CAS), and vessel control system (VCS).

Vessel Monitoring and Information System

The VTMIS facilitates ship traffic information such as the ships' position, course, speed, acceleration and trajectory conditions, so that such information can be used for navigation purposes as well as for collision avoidance among ships. Besides a scan sensor (i.e. Radar/Laser Sensor) there are three main modules: vessel detection & tracking (VDT); vessel state estimation and trajectory prediction (VSETP); inter-vessel communication (IVC).

A Radar/Laser sensor is used for vessel detection in the VTMIS. An artificial neural network (ANN) based multi-vessel detection and tracking process has been implemented on the VDT module. This detects and tracks ships navigating in the scan sensor vicinity. An extended Kalman filter (EKF) based vessel state estimation (i.e. position, velocity and acceleration) and navigational trajectory prediction process has been implemented on the VSETP module. This process is executed under the information given by the VDT module. The vessel traffic information (i.e. ship position, course, speed, etc.) transfers among ships and shore based maritime authorities could be transferred by the IVC module through a wireless network. An extensive study on the VTMIS is presented in [3].

Collision Avoidance System

The CAS generates collision avoidance decisions/actions in a sequential format that can execute on ship navigation. As presented in Figure 1, the CAS consists of four modules: own-vessel communication (OVC), parallel decision making (PDM), sequential action formation (SAF), and collision risk assessment (CRS).

The OVC module facilitates communication among ships and VTMISs. The PDM module consists of a Fuzzy logic based decision making process that generates parallel collision avoidance decisions with respect to each ship collision risk. Furthermore, that creates course and speed change decisions for ship manoeuvres, upon which decisions will be transferred to the SAF module to create proper collision avoidance actions. The rules, regulations and expert navigational knowledge

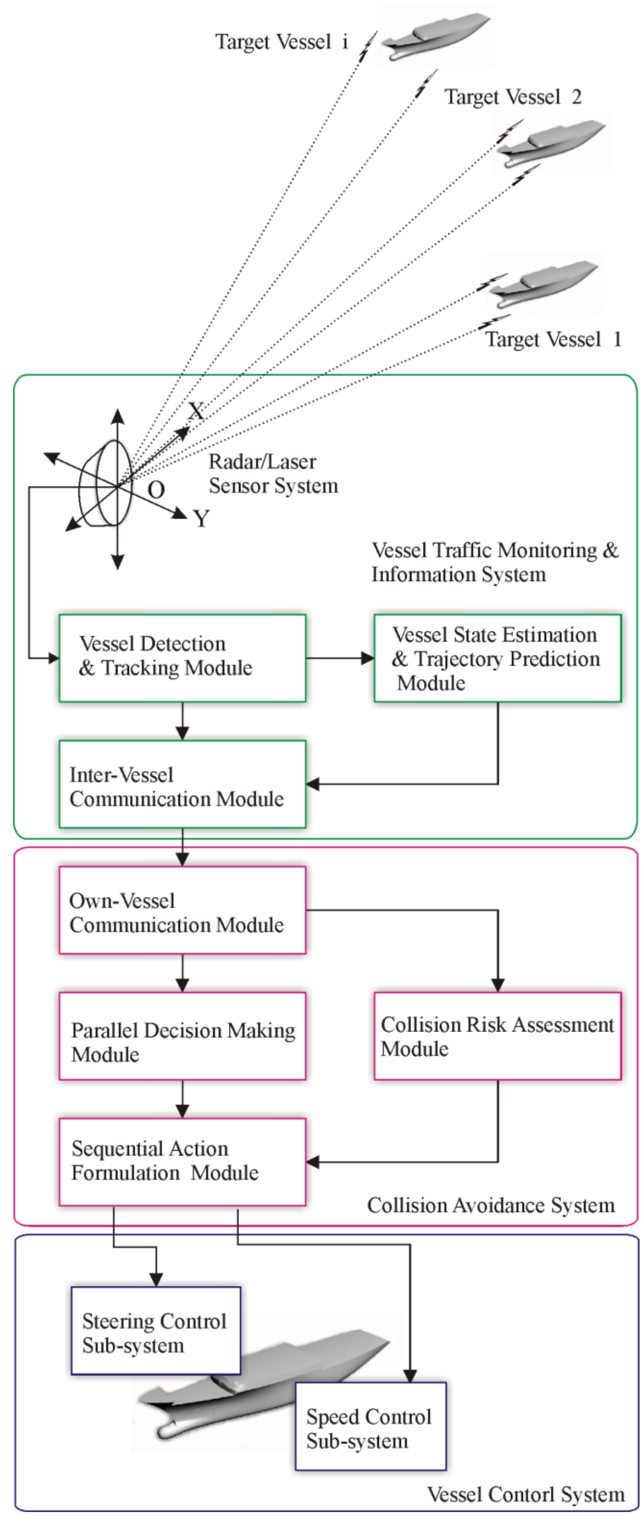

Figure 1: Mathematical Formulation of Collision Avoidance

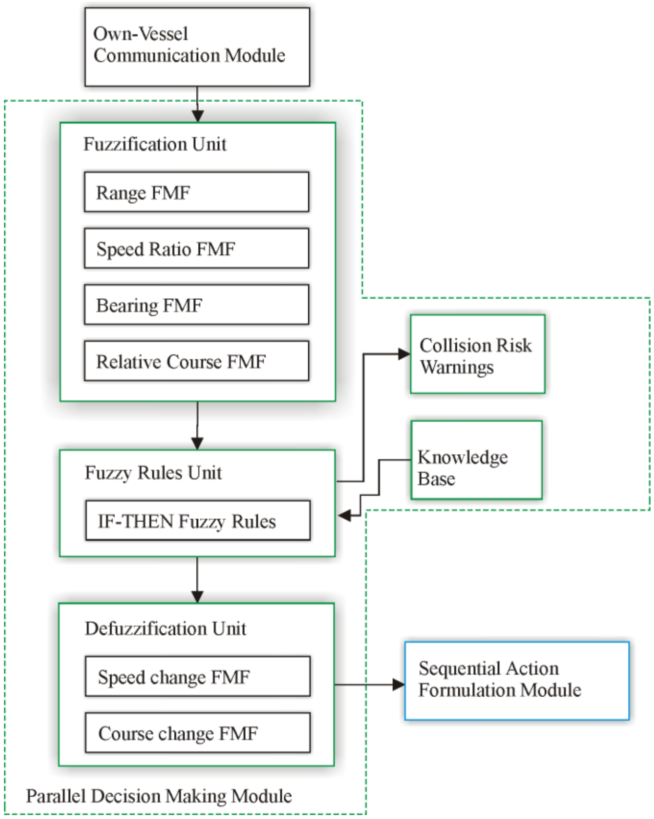

Figure 2: Parallel Decision Making Module

proposed by the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) have been considered by the PDM module. Extensive studies on the PDM module are presented in [4] and [5].

The CRA module evaluates the collision risk and expected time until collision of each ship with respect to a single ship that is called as the “Own vessel”. Such information will be transferred to the SAF module for collision avoidance actions. Extensive studies on the CRA module are presented in [6] and [7]. The SAF module organizes the parallel collision avoidance decisions that were initially generated by the PDM module into sequential actions, considering the time until collision for each collision situation estimated by the CRA module. Extensive studies on the SAF module are presented in [4] and [5].

Finally, the sequential collision avoidance actions that were organized by the SAF module will be transferred into the VCS. These actions can be categorized into two sets of course and speed controls which are implemented on ship manoeuvres. The course and speed control collision avoidance actions with respect to each situation are executed under two sub-systems: steering control sub-system (SCS) and speed control sub-system (SPS). The SCS and SPS control course and speed conditions in ship manoeuvres, respectively. One should note that the CAS and VCM are executed on the Own vessel. Considering the CAS, the PDM and SAF modules are described in following section to improve the readability of the paper

Parallel Decision Making Module

An overview of the PDM module is presented in Figure 2. The module consists of 3 main units: Fuzzification, Fuzzy rules and Defuzzification. The inputs of the OVC module, namely, range, bearing, course and speed of other ships for which there are collision risks with the own vessel at their respective time instants are Fuzzified in the Fuzzification unit. Accordingly, the following input fuzzy membership functions (FMFs) are considering: range FMF, speed ratio FMF, bearing FMF, and relative course FMF. Afterwards, the Fuzzified results will be transferred into the Fuzzy rules unit for further analysis. IF-THEN Fuzzy rules are developed in accordance with the COLREGs rules and regulations [8] and expert navigational knowledge in the Fuzzy rules unit.

The collision avoidance decisions for the own ship (i.e. with respect to the other ships that have collision risks) are generated by the Defuzzification unit. That consist of course and speed change decisions, that will be executed in the Own vessel manoeuvres. The decisions that need to be taken to avoid collision situations are considered to be the following: course change to starboard, $\delta\psi_o>0$; course change to port, $\delta\psi_o<0$; no course change $\delta\psi_o=0$; increase speed, $\delta V_o>0$; decrease speed, $\delta V_o<0$; no speed change, $\delta V_o=0$. Extensive details on Fuzzification, Fuzzy rules and Defuzzification are presented in [4].

Sequential Action Formulation Module

An overview of the SAF module is presented in Figure 3. This module consists of four nodes/units: Time until collision estimation (TUCE), Collision risk estimation (CRE), Collision avoidance action formulation (CAAF), and Action delay. The main objective of the SAF module is to transform the parallel collision avoidance decisions that are generated by the PDM module into sequential actions that can be executed in the Own vessel manoeuvres. This can be achieved by collecting the collision avoidance decisions and evaluating them using the time until collision with respect to each ship that has collision risks with the Own vessel. Then, the final results (i.e. collision avoidance actions) are arranged as a sequential formation involving the course and speed actions at the respective time instants.

The inputs of the SAF module are the collision decisions, and the collision risk generated by the PDM and CRA modules. The main objectives of the TUCE and CRE nodes are to estimate the time until collision and the collision risk, respectively, between the Own vessel and other ships. The actions delay is designed to formulate the appropriate time for executing the actions to avoid collision situations.

The CAAF node is affected by the action delay and the CRE

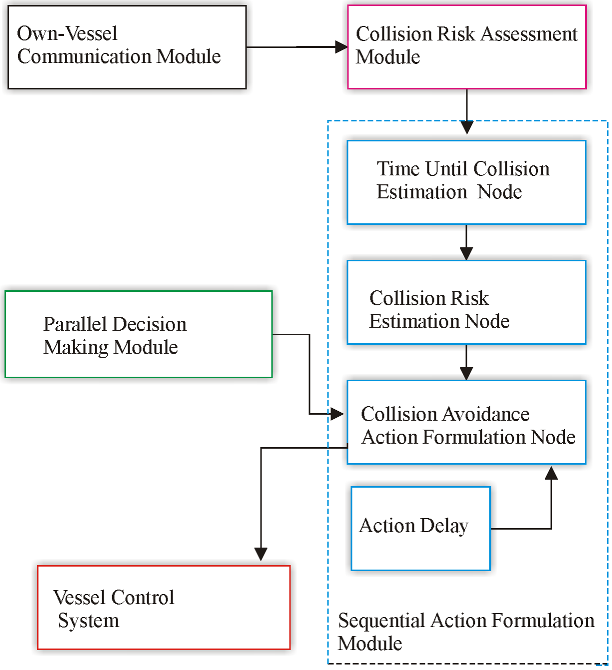

Figure 3: Sequential Action Formulation Module

nodes. The own vessel collision avoidance actions are formulated by the CAAF node. Such actions are divided into two sections: course and speed change actions which are generated by the collision avoidance decisions from the PDM module. These accumulated actions are implemented in the VCS of the Own vessel manoeuvres.

EXPERIMENTAL SETUP

Ship Model

A two vessel collision situation is considered in this study. The own vessel is implemented under a ship model that is presented in Figure 4 and another ship is simulated. The ship model characteristics are as follows: overall length of 2.590 m; length between perpendiculars of 2.450 m; breath equal to 0.430 m; depth of 0.198 m; estimated trail draft and displacement of 0.145 m and 115.6 kg, respectively. The model is built in single skin glass reinforced polyester, with plywood framings. The ship model is controlled by a navigation & control platform that is divided into the hardware structure and the software architecture.

Hardware Structure

The hardware structure consists of all sensors and actuators that are used in the navigation & control platform. This structure is further divided into the two following units: command and monitoring unit (CMU) and communication and control unit (CCU). The main objective of the CMU is to facilitate manual and autonomous control of ship manoeuvres

Figure 4: Ship model in collision acoidance manouvers

provided by a human machine interface (HMI) as presented in Figure 5. The CCU is implemented on a shore based station. The CMU mainly consists of several instrumentations such as, Laptop computer, GPS unit, and industrial WiFi unit.

The Laptop computer is used as a HMI that is connected through an industrial WiFi unit for communication with the CCU. The computer works as a data display unit as well as an automatic and manual control unit for the ship model. Furthermore, the above discussed VTMIS is implemented on this Laptop computer under MATLAB software. The VTMIS is simulated to obtain a second vessel behaviour that is heading towards a collision course with the Own vessel. This data is forwarded to the Own vessel for appropriate collision avoidance actions.

The GPS unit is used in the CMU for position measurements of the ship model. The complete GPS system has two units, namely, a base station and a rover station which are used to improve the position accuracy of the ship model. The base GPS station unit acts as a stationary reference that transmits known stationary position correction signals for the rover GPS station that is located in the ship model. The WiFi (wireless Ethernet) unit is used for communication between the ashore based CMU and the on-board CCU.

The proposed CCU is implemented on a ship model as presented in Figure 6. A major part of the CCU consists of the CAS module (i.e. Fuzzy-Bayesian based decision-action execution process) for collision avoidance among vessel and that is also associated with the course and speed controls for ship manoeuvres. The CCU has the following instrumentation/actuation; two CompacRIO units, industrial Ethernet switch (IES), Laptop computer, GPS unit, inertial measurement system (IMS), WiFi unit, and two DC motors.

Two CompactRIOs with input/output (I/O) modules are National Instruments' (NI) data acquisition systems (DAQ). One CompactRIO collects digital data from the IMS and GPS units. The other CompactRIO is connected to the steering and speed control sub-systems of the ship model in order to control

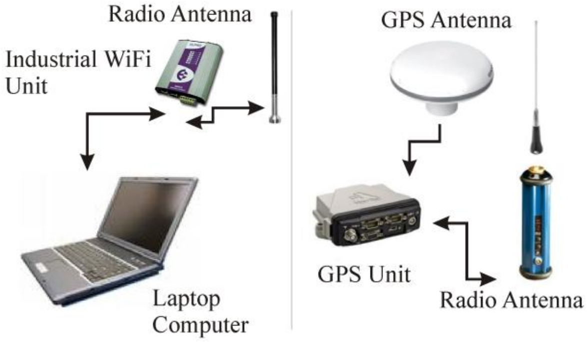

Figure 5: Command and monitoring unit

the actuations of the rudder and propeller which are assembled to two DC motors. The rudder and propeller sub-systems are associated with PID controllers. Both CompactRIOs are connected through the IES for Ethernet communication.

The Laptop computer in the ship model is used to record and store the digital data collected from the IMS and GPS units through the IES connected to the CompactRIO. Another onboard GPS unit is used in the CCU to accurately estimate the position of the ship model as discussed previously. The IMS unit consists of the following sensors: magnetometer, accelerometer, rate gyro, GPS receiver. The IMU is capable of measuring the 3-axis angles of heading, roll, and pitch, the 3-axis angular velocities of heading, roll, and pitch, the 3-axis linear accelerations of surge, sway and heave. An internal GPS receiver in the IMS unit measures the ship model position facilitated with WAAS capabilities. The IES is used in the CCU as a communication gateway among sensors, actuators, and CompactRIO units.

Furthermore, the above discussed CAS is implemented on the Laptop under MATLAB software. The CAS formulates the collision avoidance actions that are based on the second vessel collision course information that is given by the shore based VTMIS (i.e. other Laptop computer). Another WiFi unit is used for communication between the ashore based CMU and the on-board CCU connected through the uninterrupted IES.

The proposed ship model is associated with decentralized control approach where the two control sub-systems are introduced: steering control sub-system (SCS) and speed control sub-system (SPS). The SCS is associated to the rudder control system and its main objective is to maintain the appropriate vessel course during its manoeuvres. The SPS is associated to the propeller control system and its main objective is to maintain appropriate vessel speed during ship manoeuvres. PID based controllers are used for both propeller RPM and rudder positions controls. The collision course and speed change collision avoidance actions that are generated by the CRS. These actions are executed under rudder and propeller

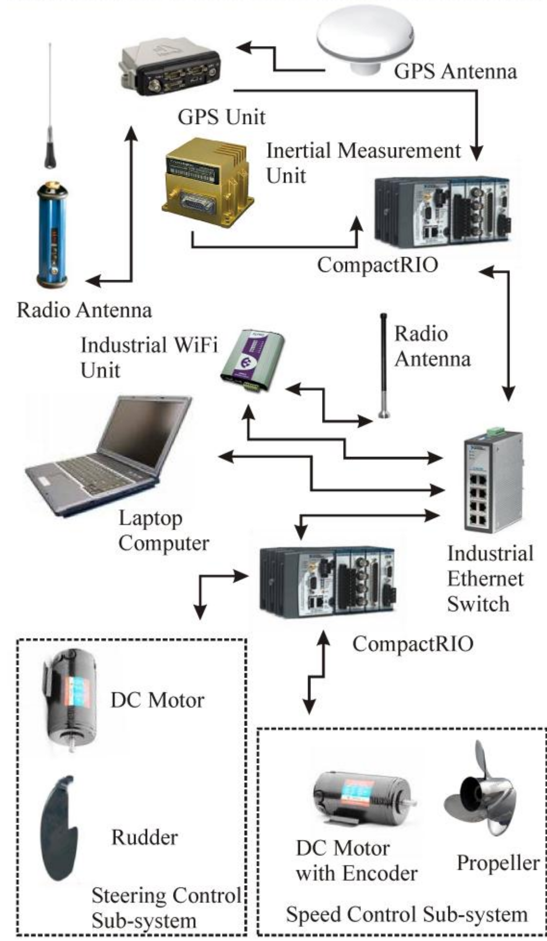

Figure 6: Comminication and control unit

control sub-systems.

Software Architecture

The software architecture is mainly programmed under LABVIEW and MATLAB and that consists of several program loops: FPGA loop, real-time control loop, CAS loop and TCP/IP loop. The FPGA loop aims at collecting data from the sensors (i.e. GPS and IMS units) and controlling the actuations of the steering and speed sub-systems. That have been programmed under LABVIEW and executed under the CompactRIO units.

The associated PID controllers for the steering and speed control sub-systems are implemented under a real-time control loop, where the internal deterministic control loop that has the highest responsiveness, determinism and priority with comparison to other software loops is designed. The data processing and saving for the respective sensors are implemented under the internal non-deterministic data processing loop that has lower priority with comparison to the deterministic control loop. The real-time control loop have been programmed under LABVIEW and executed under the CompactRIO units.

The CAS loop consists of the proposed CAS that has been programmed under MATALB and of the proposed Fuzzy-Bayesian based decision-action execution process for collision avoidance for ship manoeuvres. The CAS loop generates required collision avoidance actions of the Own vessel with respect to the simulated second vessel that is heading for a collision course. These collision avoidance actions are executed under the real-time loop associated with the steering and speed control sub-systems. The CAS loop have been programmed under LABVIEW and MATLAB and executed under the on-board laptop computer.

The TCP/IP loop is related to the communication between shore based CMU and the VTMIS. The TCP/IP loop is implemented under wireless communication through the industrial WiFi unit. An extensive overview of the experimental platform is presented in [9].

EXPERIMENTAL RESULTS

The collision avoidance experiments were conducted on the lake of "Campo Grande" in Lisbon, Portugal. These experiments involve various ship manoeuvres and two vessel collision situations. In the collision avoidance tests, the ship model with the on-board CAS as described previously has been used. However, a scaled version of the CAS has been used during these experiments due to the practical difficulties (i.e. wind and wave conditions) faced by ship model navigation. Due to the environmental conditions, sudden variations in the course and speed for the ship model have been noted and that was one of the major challenges to create a collision situation between two vessels.

In these collision situations, the Own vessel was represented by the ship model and a second vessel that has a collision course with that vessel was simulated. As mentioned before, it was observed that the formulation of a collision situation between two ships is extremely difficult to achieve due to the ship model sudden course change and speed variations caused by the wind and wave conditions. One should note that a small variation in course and speed conditions of a vessel could completely remove the collision risk between two vessels

Therefore, an additional algorithm was developed for the second ship manoeuvres. This algorithm consists of the following steps: the simulated ship is located in an initial position near the Own vessel navigation route and the algorithm searches a proper collision course with the Own vessel; when it finds it executes that course with the appropriate speed conditions. Consequently, this loop generates an appropriate collision situation between both ships.

Several collision situations between two ships were created and the appropriate actions taken by the Own vessel were recorded under such conditions. The CAS was implemented on the on-board Laptop computer as described previously. The simulated ship was implemented on the shore based VTMIS (i.e. other Laptop computer) as described previously. It is assumed that the simulated ship is moving at constant course and speed conditions and does not honour any navigational rules and regulations at sea. Furthermore, constant speed and course conditions for the simulated ship are also assumed in these experiments to keep the consistence in the collision situation.

EXPERIMENTAL EVALUATION

Collision Situation I

The first set of experimental results of a two ship collision situation is presented in Figures 7 and 8. As presented in Figure 7, the ship model and the second ship start navigation from the origin *(0 (m), 0 (m))* and from the positions *(10 (m), 20 (m))*, respectively. One should notice that the spiral section of the second ship trajectory, which is near its initial position, represents the searching algorithm that has been used to formulate a proper collision situation between two ships as described previously. As presented in the figure, the ship model has observed one possible collision situation, as the second ship approaches for a crossing collision situation from starboard. To notice that the in accordance with the COLREGs rules and regulations the ship model and the second ship are in a ”Give way” and in a ”Stand on” situation, respectively. Therefore, the ship model has taken early actions to avoid the collision situation by altering course to starboard. That can be noted in Figure 7, which represents both ships' routes.

Furthermore, the ship model (i.e. Own vessel) and second ship (i.e. Target vessel) position coordinates (x, y) with respect to time are also presented in the first and second plots of Figure 8. The collision avoidance actions of alter course to starboard and speed increment at the firth stage, alter course to port and speed increment at the second stage; alter course to starboard and speed increment at the third stage, that have been taken by the ship model are presented in the third and fourth plots of Figure 8.

Collision Situation II

The second set of experimental results of a two ship collision situation is presented in Figures 9 to 10. The ship model and the second ship start navigation from the origin *(0 (m), 0 (m))* and from the positions *(30 (m), 10 (m))*, respectively. As presented in figure 9, the ship model has observed one possible collision situation as the second vessel approaches for a head-on collision situation. However, the second vessel has not taken any appropriate action to avoid the collision, whereas the ship model is forced to take appropriate actions to avoid the collision. Therefore, the ship model has taken early actions to avoid the collision situation by altering course to port. That can be noted in Figure 9, which represents both ships' routes.

Furthermore, the ship model (i.e. Own vessel) and the second ship (i.e. Target vessel) position coordinates (x, y) with respect to time are also presented in the first and second plots of Figure 10. The collision avoidance actions of alter course to port and speed increment at the first stage, alter course to starboard and speed increment at the second stage, that have been taken by the ship model are presented in the third and fourth plots of Figure 10.

CONCLUSION

Experimental results on collision avoidance of autonomous ship manoeuvres are presented in this paper. The collision avoidance conditions are conducted on an experimental setup that has been further described in this paper. The experimental setup consists of two sections of a vessel model and a navigation & control platform and that has also been summarized. Several situations of two ship collisions are considered and the successful collision avoidance results with respect to the above system are reported. The experimental results on collision avoidance represent the superior capabilities of intelligent guidance in ship navigation and that can also be integrated into an e-Navigation environment.

ACKNOWLEDGMENTS

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The ship model manoeuvring and collision avoidance videos can be found at the URL: ***www.youtube.com/thecentec***.

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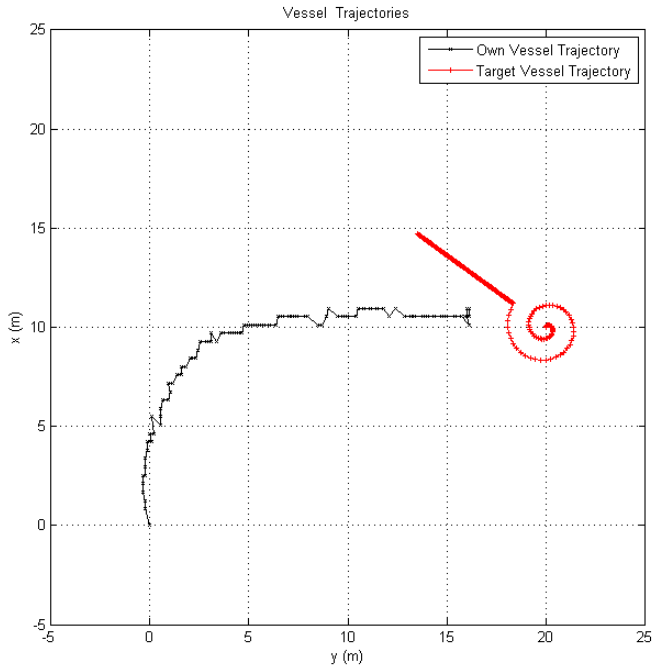

Figure 7: Collision Situation I - vessels' trajectories

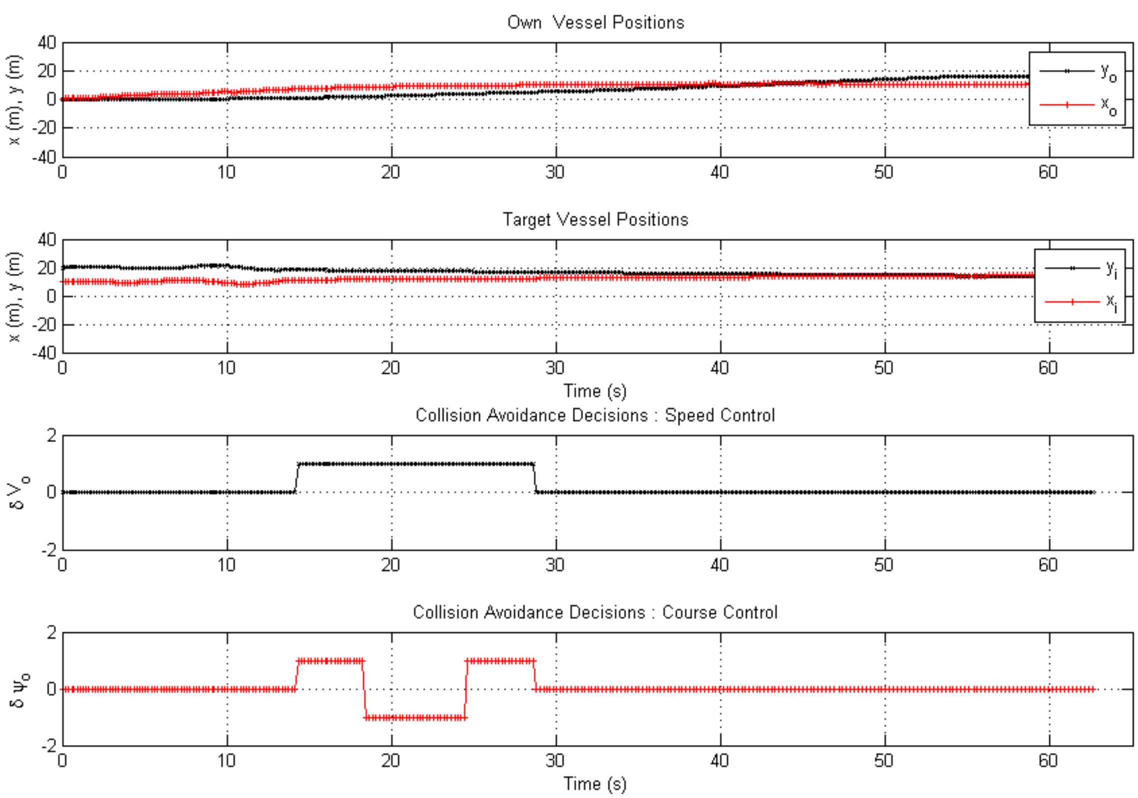

Figure 8: Collision Situation I – vessels' positions & collision avoidance decisions

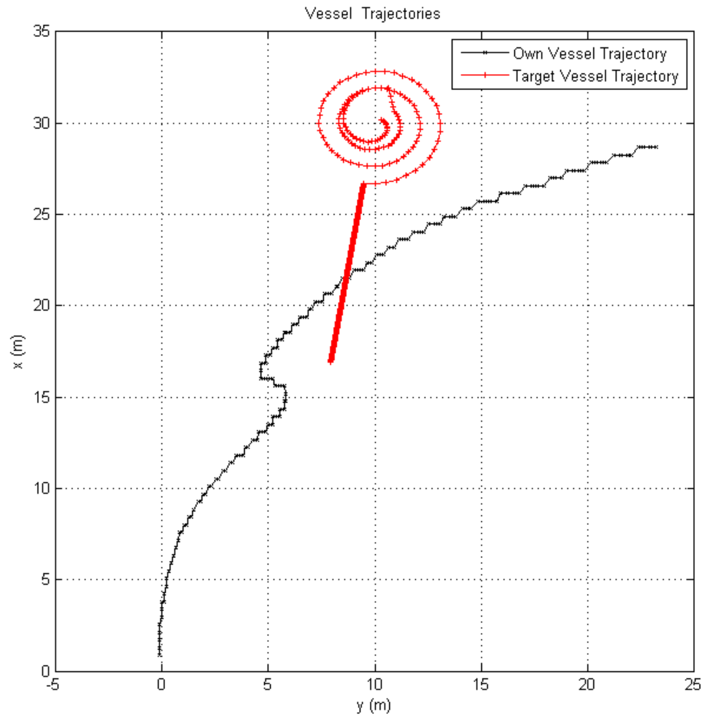

Figure 9: Collision Situation II – vessels' trajectories

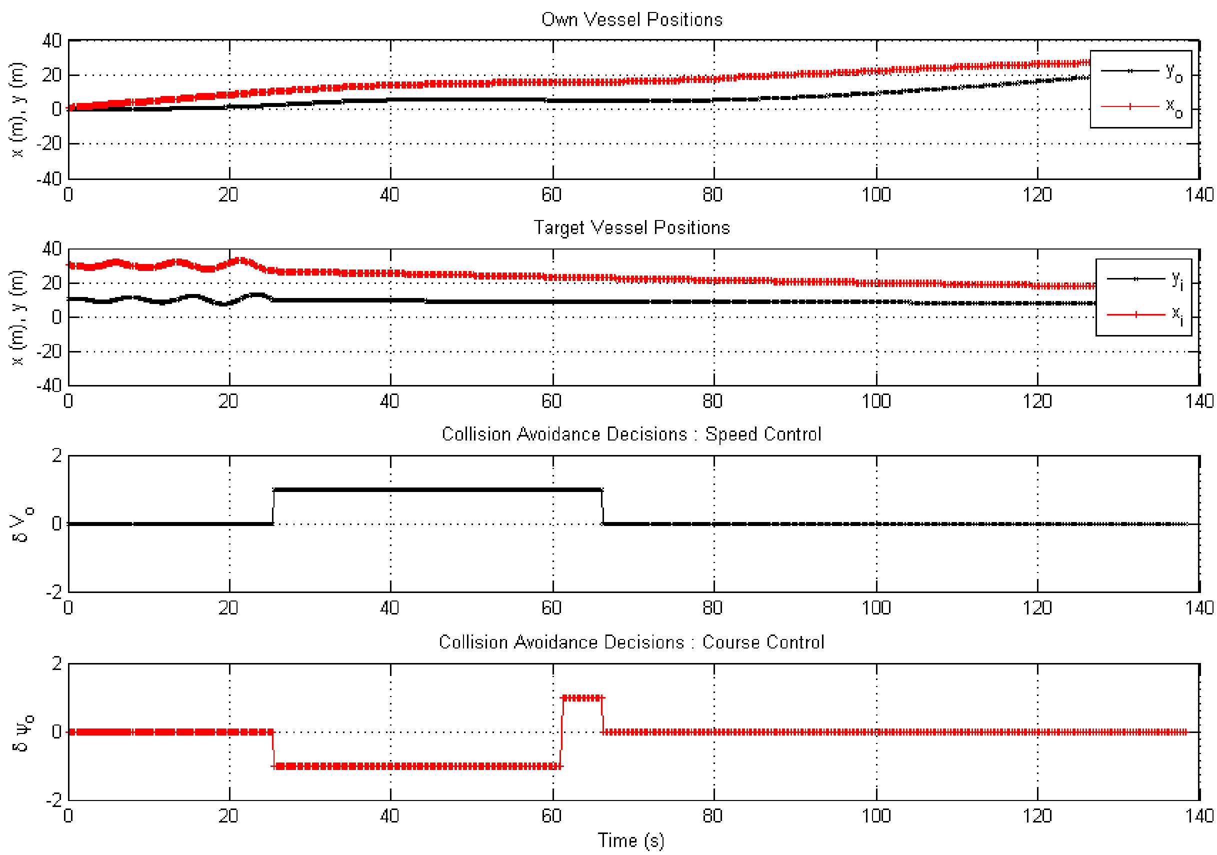

Figure 10: Collision Situation II – vessels' positions & collision avoidance decisions