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Autonomous COLREGs Compliant Ship Navigation, Using Bridge Simulators and an Unmanned Vessel

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Abstract

This paper presents an approach to COLREGs compliant ship navigation. A system architecture is proposed, which will be implemented and tested on two platforms: networked bridge simulators and at sea trials using an autonomous unmanned surface vessel. Attention is paid to collision avoidance software and its risk mitigation.

1. Introduction

As a result of rapid progress made in hardware (e.g. computer, sensors, and satellite communications) and software (e.g. autonomous navigation) in the last decades, we are witnessing the take-off of autonomous systems in a number of industries, from driverless cars, to flying unmanned aerial vehicles (i.e. drones). Autonomous systems and robotics have been identified as one of the top 8 technologies with disruptive potential, *Willets (2013)*. Despite the maritime industry being traditionally conservative, we are also seeing different types of autonomous system prototypes and operational systems, either underwater, on the surface, crawlers, or in the air. Their applications range from asset inspection, ocean exploration, unmanned mine hunters, etc. Now, the industry is gearing towards smart ships, and commercial and naval autonomous ships are being considered, *Rødseth and Burmeister (2012)*. The GMTT2030 report, http://www.lr.org/gmtt2030, discusses the technologies that will make an impact in the future maritime industry. Those include autonomous systems (and hence autonomous ships), and other relevant technologies such as smart ships, sensors, robotics, communications and big data. The drivers for autonomous ships are several, the most important of which are:

i) Safety - Studies have shown that accidents at sea are greatly caused by human errors, *IMO (2004)*. The continuous reduction in ship manning and increase in automation, especially in navigation tools, puts high demands on the crew, leading to fatigue and then human errors, *Hetherington et al. (2006)*. Human errors and wrong interpretation of the rules are responsible for many of the collision accidents *Mohović et al. (2015)*. Autonomy and autonomous navigation in particular, will contribute to reduce human errors, by offloading the crew from some of their highly demanding tasks and enforcing rules compliance, thus increasing maritime safety.
ii) Financial - Autonomous ships, with less or no manning, will reduce operational costs. Although investment and shore costs might be higher.
iii) Social - Autonomous ships will compensate for the scarcity of sufficiently qualified seafarers.

Autonomy is the degree of decision making deferred from the human to the system and is a continuum or spectrum rather than being binary in nature. Autonomy levels range from remotely operated to fully autonomous systems. Note that the terms unmanned and autonomous ships are often interchanged, but they are not the same. An unmanned vessel could be remotely operated, and it's therefore not autonomous; while an autonomous ship could be manned. Autonomous navigation is one important step towards ship autonomy, but there are additional tasks carried out by the crew, e.g. maintenance, cargo-handling.

This paper discusses the work being done in the MAXCMAS (“MAchine eXecutable Collision regulations for Marine Autonomous Systems”) collaborative research project, which aims at developing robust COLREGs (International Regulations for Preventing Collisions at Sea, *IMO (1972)*) compliant machine executable autonomous navigation. COLREGs are the "rules of the road" defined by the International Maritime Organization (IMO) which provides a set of rules to prevent collisions between two or more vessels. The project consortium consists of Rolls Royce (RR) as project lead, Atlas Elektronik UK (Atlas), Southampton Solent University’s Warsash Maritime Academy (WMA), Queen’s University Belfast (QUB) and Lloyd’s Register (LR). The partners bring their technical expertise in a number of relevant areas: RR in systems engineering, vessel and equipment expertise; Atlas in control system integration, simulation and at-sea testing, naval vessel design and unmanned systems design; WMA in high fidelity simulation, seafaring expertise and human factors; QUB in unmanned systems R&D, navigational decision making and machine cooperative behaviour; and LR in risk management, assurance, dissemination and cost-benefit analysis. The project is at an early phase, and only the approach will be discussed here.

2. System architecture and requirements

Fig. 1 shows the system architecture. It combines sensors and data fusion, autonomy software (also known as autonomy executive), a collision avoidance algorithm, and a controller interface, into two platforms:

i) a networked bridge simulator environment, that will allow testing the system under a number of collisions scenarios, with autonomous, as well as manned vessels of different types, varying weather conditions, including poor visibility;

ii) the ARCIMS USV mine hunter, where the system will be tested during actual sea trials in a controlled environment. https://www.atlas-elektronik.com/what-we-do/mine-warfare-systems/arcims/

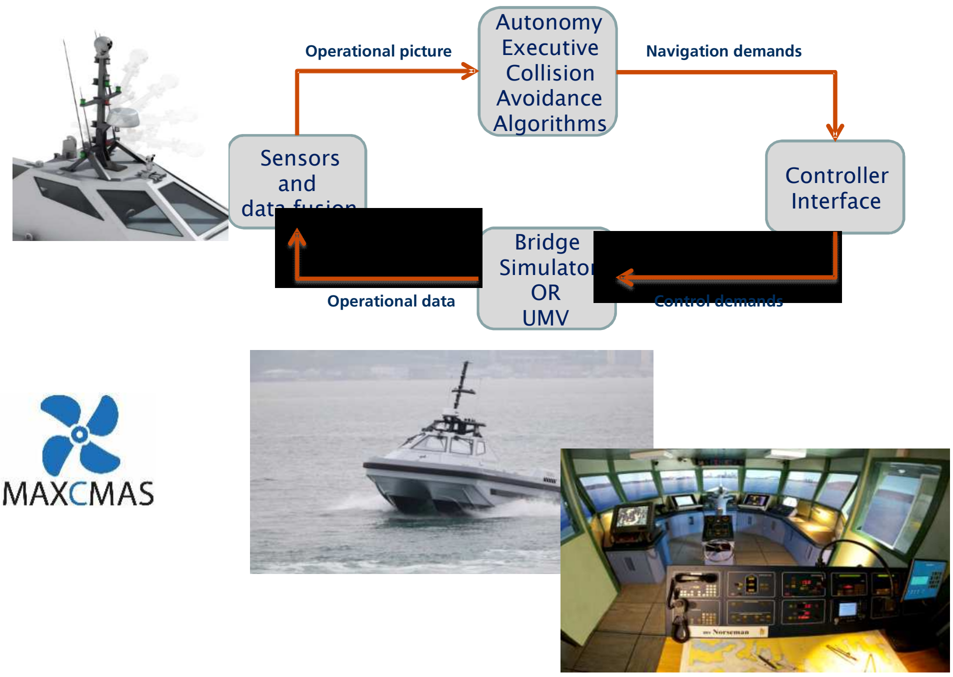

Fig. 1: MAXCMAS system architecture: (top-left) ARCIMS sensors; (bottom-right) Warsash bridge simulator; (bottom-left) ARCIMS USV

Autonomous navigation relies on data obtained from sensors (radar, electro-optic cameras and AIS) about the vessel environment, and data about the own vessel status. The data is combined using data fusion techniques, giving an operational image. The environmental information, together with the own vessel data (speed, engine status, etc), is passed to the autonomy executive/collision avoidance algorithm, which then translates it into navigational demands (speed, heading). The controller interface translates it into throttle/rudder demands for the vessel (simulated or real).

System requirements have been defined in order to comply with COLREGs and good seamanship practice. A significant challenge is to translate the COLREGs (41 rules and 4 annexes), which were written for human consumption, into requirements for autonomous vessels, in the form of state of the art collision avoidance algorithms and sensors. In total more than one hundred requirements have been derived. For example, Rule 5 states “Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision”. Compliance with Rule 5 for an autonomous vessel has implications in terms of requirements for the sensors, sensor processing system, picture compilation and collision avoidance. Similarly other requirements are derived by compliance with the other COLREG rules. Additional requirements are imposed on the system, e.g. the collision avoidance system should be scalable from small to large vessels of varying manoeuvring capabilities.

3. Path planning and collision avoidance

Typically a collision avoidance system consists of a risk assessment unit, a decision maker and a path planner. At the start of navigation, a mission is planned consisting of a predefined set of waypoints, based on a known map of an environment. Risk is assessed regularly and/or whenever a target ship is detected in the vicinity by the on-board obstacle detection module, Fig. 2. The mission plan is updated by the path planner should a risk be deemed to exist.

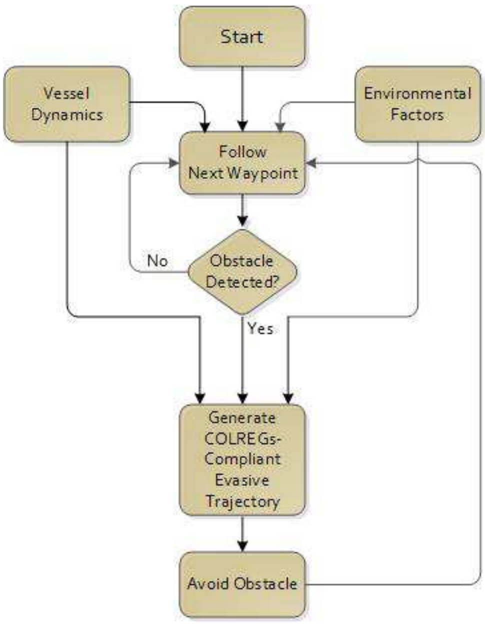

Fig. 2: Flowchart of a generic COLREGs-based path planner

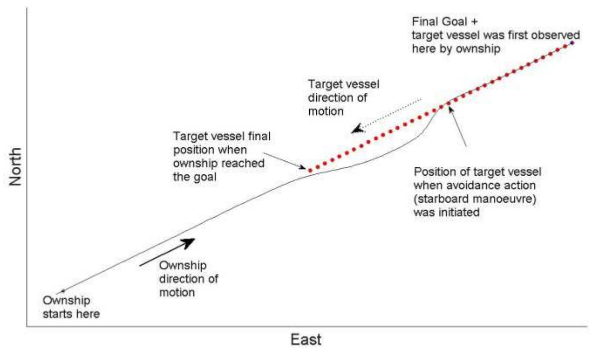

Fig. 3: Own ship trajectory showing successful head-on collision avoidance

The risk assessment primarily works on the principle of estimating the closest point of approach (CPA) which is defined as an estimated point at which the distance between two ships, of which at least one is in motion, will reach its minimum value. It is assumed that vessels will continue their current speed and heading. Assessing risk through estimating the CPA or to be precise TCPA (time to CPA) is a commonly employed method by mariners. For multiple target vessels in low traffic areas, it is usual to consider the risk sequentially meaning that the vessel with the lowest TCPA will be dealt with first. For an autonomous vessel, however, the challenge is to decide an appropriate course of action once a risk is deemed high or when multiple COLREGs apply.

A software-based decision maker plays a key role in automating a collision avoidance system. The functions of a decision maker include but are not limited to deciding whether a course of action (change of course or speed) is needed; what COLREGs rule (if any) is applicable; and whether multiple COLREGs would apply.

As shown in Fig. 2 a vessel normally follows waypoints from her navigational plan and only deviates from the path when a risk of collision is confirmed. It is important that the evasive path is COLREGs-compliant so that the own-ship behaves in a 'human-like' manner which would not cause any confusion or concerns for target ships in the vicinity. A rule-based repairing A* (RR-A*) algorithm was developed earlier, *Campbell et al. (2012)*, to handle the three fundamental COLREGs rules including head-on, crossing and overtaking scenarios. A head-on situation is illustrated in Fig. 3 where an own-ship undertakes a starboard manoeuvre (COLREGs Rule 14) in order to avoid colliding with an oncoming vessel. Note that although the target ship does not adhere to COLREGs by altering course to starboard, the own vessel must follow the collision regulations at all times.

4. Bridge simulator trials

The simulation tests will be performed using a network of six highly immersive bridge simulators at WMA (Warsash Maritime Academy Warsash Maritime Academy), conventionally used for mariner training. These will be employed to demonstrate the human reaction from the crew of a virtual vessel encountering a synthetic autonomous vessel. The autonomous ship mechanism, Fig. 1, will be installed in one of the conventional bridges. This synthetic autonomous vessel may interact with one or more manned bridge simulators, and/or other simulated target ships following predefined routes.

The simulator experiments will be run in a series of sessions, the results of which will allow refining the collision avoidance algorithm and verifying that the system requirements are met (Section 2). A variety of scenarios will be designed ranging from basic level single vessel encounters to more complex level multi-ship situations and these will be included in a simulator protocol to ensure all scenarios are run consistently. With this aim in mind, the MAXCMAS scenarios have been categorised into the following 5 levels:

i) Basic: Open water exercises involving encounters with one or two target ships.
ii) Intermediate: Exercises involving multi-ship encounters when approaching a coastline or other navigational hazard from open waters.
iii) Advanced: Intensive exercises involving the approaches to and passage through areas of heavy traffic with navigational restrictions.
iv) Good seamanship: Ordinary good practice of seamen with due regard to the application and observance of COLREGs which may be required while navigating a ship.
v) Breakdown: Navigation during an emergency situation and sensor degradation.

Together with this particular autonomous bridge, there will be test runs by one or two manned bridges. These simulated manned bridges could be combined with either target ships or run in parallel with the autonomous ship so that manned vessel(s) and autonomous vessel encounter the same challenges in similar environmental conditions. The experiments can be potentially progressed up to 5 manned bridges to develop very complex scenarios to comply with the test requirements. However, the real challenge will be the implementation of the safety measures which may be required by good seamanship practice i.e. to avoid any navigational danger during any special circumstances. As it is known a good level of seamanship may be needed for the practical application of the COLREGs and it is normally gained through training and long experience. Seamanship is a huge challenge for developing the machine interpretation algorithms, and feedback from experienced mariners will be obtained by means of questionnaires. A full interaction of weather conditions will be introduced in these scenarios, in different simulated operating areas (Portland Harbour, UK; and San Francisco Bay, USA) and different own-ship models, with emphasis on understanding their handling. During the scenario trials, every vessel will use common sensors (e.g. gyro, AIS, GPS, radar) and these driving sensors will initially test the algorithms using noise-free sensor information and later the scenarios will be tested with the degraded sensor(s).

The minimum qualifications of personnel on the manned bridges will be navigating officers holding at least the OOW CoC (Officer of Watch Certificate of Competency) in the Level 1 & 2 scenarios and the Chief Mate/Master in Level 2 to 5 scenarios. Potentially both subjective (e.g. performance criteria) as well as objective assessment criteria (e.g. weighted scoring of CPA/TCPA, variables, track parameters) for each scenario will be developed and included in the simulator protocol. The objectives of such a methodology are to empower the structured evaluation of simulator recorded scenario performances against the benchmark criteria/scores.

5. USV sea trials

The sea trials will done using the 11m ARCIMS USV platform (designed and owned by Atlas Elektronik UK), equipped with the autonomy system described in Fig. 1. Sea tests will be coordinated from the Bincleaves waterfront facility at Portland Harbour, Dorset (UK). The USV sea trials, along with both desktop and Warsash based simulator trials, will serve to verify the system requirements, in a controlled sea environment and three different setups.

(i) Mixed reality. In “mixed reality” testing, the real vehicle will be used on the water for the first time, but all its collision avoidance targets remain simulated. This will allow the real vehicle dynamics to be tested, and conclusions drawn about how representative of them the software simulation models were. Targets will be added to the system by an operator, and the vehicle will avoid them in open water so that it won’t (at this stage) need to operate in close quarters with any other vessels.

(ii) Real target with perfect knowledge. The next step is to introduce a real vehicle (or several) as avoidance targets. This will verify that the avoidance still works correctly when the targets move in non-idealized ways (e.g. bobbing back and forth, not following straight lines). Each target boat will be tracked with a GPS receiver and a communications link to the ARCIMS USV, so the avoidance algorithm has “perfect knowledge” of the target position, course and speed.

(iii) Platform full sense and avoid tests. The final step is to use the sensors on the ARCIMS platform. The sensors will also be independently tested in parallel to ensure they perform as expected and produce reliable, usable track outputs. The USV will then avoid the target boats and static targets using its own sensor capability. A wide variety of real-world scenarios will be demonstrated to ensure the vehicle behaves correctly under the many different circumstances it could encounter.

Tests will be performed against static and moving vessels in overtaking, head-on and crossing encounters in which the autonomous vessel is the give way and stand-on vessel and the encountered vessel acts as expected and otherwise. These scenarios can be tested for multiple moving and static targets in open water and where a coast line bounds the available space to manoeuvre. For the purposes of the MAXCMAS project the bounded scenarios will be limited to the water space at Portland Harbour (where ARCIMS platform testing will occur) and San Francisco Bay (desktop simulations), as in the bridge simulator tests (Section 4).

6. Risk mitigation and software assurance

Collision avoidance performs a safety related function since its ultimate goal is to avoid incidents that may result in loss of life, asset damage and pollution. Successful collision avoidance can be achieved if several safety barriers are put in place encompassing operational as well as technological aspects. This is shown in Fig. 4, where each layer represents one or several elements that may prevent the occurring of a collision scenario and hence mitigate risk. The highest layer highlights the fact that thorough mission and navigation planning before the commencement of the mission is fundamental since it will identify potential threats such as busy shipping lanes, shallow waters and isolated obstacles in advance. Mid layers such as observers and real time re-planning algorithms, i.e. collision avoidance system, come subsequently, since their role is to continuously analyse the situational awareness picture, identify potential collisions situations and rearrange the route accordingly, while the mission is already underway. The lowest layer is the ultimate collision avoidance measure, one or several very reactive manoeuvres, which have to be identified and executed if the above safety barriers have been breached.

Highest layer: initial mission and navigation planning
Mid layers: real time re-planning (e.g. collision avoidance system)
Lowest layer: very reactive emergency/evasive manoeuvres and procedures (e.g. stop or full ahead)

Fig. 4 Layers or safety barriers for collision avoidance

In the context of autonomous navigation, the mid and lowest layers are done by the system without human intervention, while the highest layer would normally still be done by a person. The scope of the MAXCMAS project is the mid layer. The observers are the sensors, and real time re-planning is done autonomously following the principles of safe navigation described by the COLREGs, as described earlier (Section 3). However, all the appropriate risk mitigation measures categorized in Fig. 4 have to be identified in addition to the real time re-planning (collision avoidance) system to define a complete risk picture and assign, if necessary, any requirements to each identified layer. To this end, the following actions will be taken: system architecture analysis, functional failure analysis (FFA), software assurance and identification of relevant collision scenarios. The analysis of the system architecture includes a high level evaluation of the re-planning algorithm and represents a valuable preparation activity for the FFA session. The scope of the FFA session is to identify and categorize all the relevant functional failure modes of the collision avoidance system and their subsequent consequences on safety aspects. As a result, specific safety requirements are defined and set on parts of the system as well as operational aspects such as sea state limitations or abort mission circumstances. The re-planning algorithm is a key component of the collision avoidance system and hence the safety requirements may result in software quality requirements set upon the re-planning as well as other key software components identified during the FFA. In order to meet these requirements, the collision avoidance software will be developed following best software assurance standards. Even though no specific standards has been chosen, the principles set by standards such as the IEC 61508-3 (process industry), the EN 50128 (railway) and the IEC 62061 (safety of machinery) will be applied. These principles may include, for instance, the V-model for software development. Finally, relevant collision scenarios will be identified, from historical reviews of incidents as well as discussions with experienced seafarers for simulation and testing purposes; and to assess the risk of collision at sea in autonomous ship navigation.

7. Conclusions

This paper has discussed our MAXCMAS approach to COLREGs compliant autonomous navigation. The system will be implemented, tested and validated later in the project, on two platforms: bridge simulators and the ARCIMS USV during sea trials. For this purpose, a number of scenarios will be tested, which will serve to prove that the requirements derived from the COLREGs and good seamanship practice are met. The scenarios will have different levels of complexity, including multi-vessel encounters, areas of heavy traffic and difficult manoeuvrability and emergency situations. Simulation testing has a number of advantages over real tests, allowing us to try many different cases under repeatable environmental conditions, in an inexpensive, fast and realistic way. Further validation will be done with the ARCIMS USV trials in a controlled sea environment, which will be tested in different encounter scenarios and three different setups, i.e. mixed reality, real targets with perfect knowledge, and real targets with limited knowledge from the USV's sensors. Emphasis has been placed on the risk identification and mitigation, including the development of the collision avoidance software following the software assurance best practices.

The project partners aims at commercializing the MAXCMAS technology. A number of applications and markets have been identified:

Unmanned Surface Vehicles

- A0. Its first direct application will be to improve the autonomous navigation capability of the ARCIMS USV. The technology could be applied to the fast growing market of USV in various marine industries, such as defence, offshore, ocean exploration and shipping (e.g. ship inspection with USVs).

Commercial and naval ships

- A1. A short term potential application of this technology would be provide assistance to the officer of the watch (OOW), by giving route recommendations to avoid collision, integrated in either ECDIS or Integrated Navigation System, alongside an obstacle detection warning system.
- A2: A second application of MAXCMAS would be for autonomous navigation under human supervision, like a smart COLREGs compliant track-pilot with collision avoidance capabilities. The OOW would be on stand-by and could intervene when deemed necessary. These two applications would contribute to improving safety of ships by reducing human errors. The drawback is that there would not be operational savings, since the level of manning would still be the same.
- A3: Another potential application, and where the potential economic benefits could be greater, is on unmanned ships, however many challenges remain to be solved.

Rules, standards and certification

- A4. MAXCMAS offers the opportunity to better understand the technologies and the risks and mitigation measures associated with autonomous vessels and autonomous navigation in particular. This will allow developing and improving rules and standards necessary for the certification of USVs and autonomous ships, to guarantee their safe operation.

Unmanned ship navigation poses many challenges: technological, regulatory, social, legal, etc. From a technology view point, unmanned ships will require all crew traditionally performed by the crew, e.g. navigation, maintenance, cargo-handling, berthing, will be done autonomously, for example with the use of robotic systems, http://www.lr.org/gmtt2030, or automatically. Stakeholders, such as ship owners, regulators, society, seafarers, will oppose the unmanned ship, if their perceived risk (in terms accidents, jobs losses, and other undesirable consequences) is greater than its potential benefits (e.g. economic savings). The economic argument for unmanned ships, including their risk cost, is being investigated as part of the project.

In the short to medium term, it is expected that small steps in the "autonomy ladder", and applications like S0-S2, are likely to occur. These will provide smart ships with greater autonomy, making them smarter, while the future of unmanned ships will need further research and convincing.

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