Received: 29 March 2019 | Revised: 14 October 2019 | Accepted: 16 October 2019
DOI: 10.1002/rob.21919

FIELD REPORT

WILEY

Autonomous maritime collision avoidance: Field verification of autonomous surface vehicle behavior in challenging scenarios

D. K. M. Kufoalor[1] | T. A. Johansen[1] | E. F. Brekke[1] | A. Hepsø[2] | K. Trnka[2]

[1]Center for Autonomous Marine Operations and Systems, Department of Engineering Cybernetics, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

[2]Maritime Robotics AS, Trondheim, Norway

Correspondence
D.K.M. Kufoalor, Center for Autonomous Marine Operations and Systems, Department of Engineering Cybernetics, Norwegian University of Science and Technology (NTNU), O.S. Bragstads plass 2D, N-7491 Trondheim, Norway.
Email: kwame.kufoalor@ntnu.no

Funding information
Norges Forskningsråd, Grant/Award Numbers: 223254, 244116/O70

Abstract

We present results from sea trials for an autonomous surface vehicle (ASV) equipped with a collision avoidance system based on model predictive control (MPC). The sea trials were performed in the North Sea as part of an ASV Challenge posed by Deltares through a Dutch initiative involving different authorities, including the Ministry of Infrastructure and Water Management, the Netherlands Coastguard, and the Royal Netherlands Navy. To allow an ASV to operate in a maritime environment governed by the International Regulations for Preventing Collisions at Sea (COLREGs), the ASV must be capable of complying with COLREGs. Therefore, the sea trials focused on verifying COLREGs-compliant behavior of the ASV in different challenging scenarios using automatic identification system (AIS) data from other vessels. The scenarios cover situations where some obstacle vessels obey COLREGs and emergency situations where some obstacles make decisions that increase the risk of collision. The MPC-based collision avoidance method evaluates a combined predicted collision and COLREGs-compliance risk associated with each obstacle and chooses the 'best' way out of dangerous situations. The results from the verification exercise in the North Sea show that the MPC approach is capable of finding safe solutions in challenging situations, and in most cases demonstrates behaviors that are close to the expectations of an experienced mariner. According to Deltares' report, the sea trials have shown in practice that the technical maturity of autonomous vessels is already more than expected.

KEYWORDS
marine robotics, motion planning, obstacle avoidance

1 | INTRODUCTION

Autonomous collision avoidance is at the core of the research and development efforts made towards autonomy in maritime navigation. A key question is whether autonomous vehicles (manned or unmanned) can safely operate in a maritime environment dominated by human-operated vehicles, and therefore governed by the current "rules of the road". Unless new rules are developed for autonomous vehicles, any autonomous collision avoidance strategy applied in real maritime traffic must adhere to the International Regulations for Preventing Collisions at Sea (COLREGs; IMO, 1972).

In the quest for an answer to the question above, authorities in the Netherlands, together with Deltares (an independent institute for applied research in the field of water and subsurface), invited selected companies to undergo a verification exercise in the Dutch North Sea to demonstrate and validate the capabilities of autonomous surface vehicles (ASVs). The results of the verification exercise are intended to be used as a supporting material for the Netherlands Rijkswaterstaat's initiative to replace manned vessels with unmanned vessels for monitoring water quality in the Dutch North Sea. The goal of the Dutch initiative is to achieve an efficient, safe, and sustainable water monitoring program through the use of autonomous measurement platforms (Verheul, 2017, 2018). The success of the verification exercise will therefore speed up the acceptance and implementation of the desired autonomous water monitoring program.

Maritime Robotics AS was among the companies invited to the Netherlands for the ASV verification exercise. Telemetron, which is Maritime Robotics' research and development vessel was therefore prepared for a test week in the North Sea, from November 20 to 24, 2017. In close collaboration with the Norwegian University of Science and Technology (NTNU), Maritime Robotics equipped Telemetron with the model predictive control (MPC)-based collision avoidance strategy described in Hagen, Kufoalor, Brekke, and Johansen (2018) and Johansen, Perez, and Cristofaro (2016). Since its first implementation and deployment on the Telemetron vessel in 2016, the MPC strategy has been tested and refined through experimental field work consisting of several campaigns in the Trondheimsfjord in Norway. Moreover, extensive field tests were carried out before the autonomous vehicle, Telemetron, was transported to the Netherlands for the verification exercise.

Since field reports available on testing COLREGs-compliance of autonomous collision avoidance methods are mainly based on the designer's/researcher's own planned experiments (see, e.g., Benjamin, Leonard, Curcio, & Newman, 2006; Hagen et al., 2018; Kufoalor, Wilthl, Hagen, Brekke, & Johansen, 2019; Kuwata, Wolf, Zarzhitsky, & Huntsberger, 2014; Schuster, Blaich, & Reuter, 2014; Svec et al., 2013) the Dutch verification exercise was a unique opportunity to validate the performance of collision avoidance methods in real maritime traffic, under the direction of experienced independent authorities. Bloot Nautical Consultancy was tasked by the Netherlands Directorate-General for Maritime Affairs to design a test plan for the verification exercise, whereas the Royal Netherlands Navy was responsible for the actual test validation process during the test week.

The maritime domain is characterized by several factors, including a large variety of obstacles, uncertain obstacle motion, complex interactions between vessels, and varying sea states. However, most of the existing field reports focus on passive obstacle behaviors in controlled environments and ideal weather conditions. The field trials reported in Benjamin et al. (2006), Schuster et al. (2014), and Svec et al. (2013) cover a few basic COLREGs scenarios, involving low-speed (<3 m/s) and close-range encounters with a single-obstacle vessel. Some complex single and multidynamic obstacle scenarios are reported in Hagen et al. (2018), Kufoalor et al. (2019), and Kuwata et al. (2014). Apart from the reports of Hagen et al. (2018) and Kufoalor et al. (2019), field testing in varying and challenging weather conditions does not seem to be part of the validation process of autonomous maritime collision avoidance methods.

As revealed by the first DARPA Grand Challenge (Buehler, Iagnemma, & Singh, 2007) and several competitions in the maritime domain (e.g., The Microtransat Challenge; Microtransat, 2019), verification exercises outside the control of robotics researchers usually demonstrate that algorithms and robot systems that function perfectly in simulations or controlled experiments are not always effective in the real world. Therefore, an important motivation for participating in the Dutch verification exercise was to uncover important aspects of maritime autonomous collision avoidance that should direct further work and future research efforts.

This paper presents and discusses the field results achieved using a collision avoidance method based on MPC. The discussions focus on important factors that must be considered to achieve COLREGs-compliance in challenging dynamic scenarios. The field test approach used during the verification exercise deviates from the typical approach used in research experiments, where test scenarios are usually limited to fixed preplanned behaviors of obstacle vessels. By adapting scenarios on the fly, challenging situations that developed due to an unexpected change in obstacle behavior were explored in the sea trials. This test approach, which considers spontaneous/unrehearsed changes in obstacle behavior, may be adopted by researchers for field testing and benchmarking of maritime collision avoidance methods.

The remainder of this paper is structured as follows. We discuss relevant aspects of COLREGs in Section 2, with focus on the test plan used during the sea trials. Section 3 describes the ASV and the system architecture used for autonomy and remote control. Section 4 provides a description of the collision avoidance strategy before the results from the verification exercise are presented in Section 5. We discuss our observations and important lessons learned in Section 6, and we provide concluding remarks in Section 7.

2 | REQUIRED VESSEL BEHAVIOR ACCORDING TO COLREGS

An important goal of the sea trials was to test scenarios that verify the capability of an ASV to safely navigate autonomously in the North Sea (Verheul, 2017). Since no special rules and regulations existed for autonomous vehicles at the time of the tests, the main task of the ASV was to demonstrate compliance to the existing "rules of the road", COLREGs (Cockcroft & Lameijer, 2012; IMO, 1972), which is applicable to all marine vessels in the North Sea. Moreover, the ASV's behavior should meet the expectations of experienced mariners, in this case two Commander Lieutenants-at-sea (LTZ 2) from the Royal Netherlands Navy. Note that COLREGs was written for the human operator, and it is not straightforward to apply some aspects to an autonomous vessel. However, through a careful design of scenarios, it is possible to perform tests that reveal the ASV's "sense of responsibility" (Rule 2), situational awareness capabilities (Rule 5), evaluation of collision risk (Rule 7), and collision avoidance action plan (Rules 6, 8, and 13–19). The rules from COLREGs considered in the verification exercise are discussed in this section.

2.1 | COLREGs

2.1.1 | Responsibility

Rule 2 of COLREGs holds all marine vessels responsible for their actions in both ordinary and special circumstances. All vessels are tasked to do everything possible to avoid collision, and if necessary, depart from the rules to avoid immediate danger. This rule requires a "sense of responsibility" that should also govern the collision avoidance strategy of the autonomous vessel. The ASV's sense of responsibility can be demonstrated/observed through its choice of actions, which should preferably be proactive.

2.1.2 | Situational awareness

Both Rules 2 and 5 emphasize the importance of understanding different situations in the maritime environment. Rule 2 states that "*due regard shall be had to all dangers of navigation and collision and to any special circumstances, including the limitations of the vessels involved*," and Rule 5 states that "*every vessel shall at all times maintain proper lookout by sight and hearing as well as all available means appropriate in the prevailing circumstances and conditions so as to make appraisal of the situation and of the risk of collision.*"

For an autonomous vehicle, these rules demand an appropriate system for accurate detection, identification, classification, and prediction of the effect of different factors in a complex dynamic maritime environment.

2.1.3 | Evaluation of collision risk

On the basis of the vessel's knowledge of a particular situation, an appraisal of the situation must be made and the risk of collision must be assessed as mentioned in Rule 5. This requirement is reemphasized in Rule 7, which states that "*every vessel shall use all available means appropriate to the prevailing circumstances and conditions to determine if risk of collision exists.*" Further specifications in Rule 7 highlight the challenging aspects of risk assessment, where emphasis is put on the appropriate assessment of scanty information. For an automatic decision process to be possible, we need a useful way of quantifying risk based on possibly uncertain information.

2.1.4 | Collision avoidance actions

Rule 8 specifies the general behavior strategy every vessel should have and the required actions in dangerous situations. First of all, "*any action taken to avoid collision shall be taken in accordance of the Rules.*" Recall that the rules cover both proactive and reactive actions. Moreover, Rule 8 focuses on the properties of proactive actions, which include early and clear (i.e., large enough) alteration of course or speed intended to control a situation.

Controlling a situation at sea involves having due regard to the observance of *good seamanship* (see Rule 8(a)). In other words, the actions made should not make the situation worse for any other vessel in the vicinity. This clearly demands the complex task of understanding a situation from the perspective of both the own vessel and other vessels. Nevertheless, making early actions according to the rules will provide other vessels ample time to also choose actions aimed at reducing the risk of collision.

Required actions in different scenarios are specified in Rules 9–19 of COLREGs. Some of the actions verified during the sea trials are applicable to power-driven vessels at sea (i.e., IMO, 1972, Rules 13–19). An illustration of some basic scenarios can be seen in Figure 1.

2.2 | Complex collision avoidance scenarios

In a dangerous encounter between two vessels, the give-way vessel is required to keep out of the way of the other vessel by altering its course and/or speed to pass the other vessel at a safe distance (see IMO, 1972, Rule 8(f.i) and 16). The stand-on vessel is required to keep its course and speed (cf., Rule 17(a.i)). However, if the give-way vessel is not taking appropriate action in compliance with the rules, the stand-on vessel may take action to avoid collision (see Rule 17(a.ii)). The stand-on vessel is also obliged to take action when the

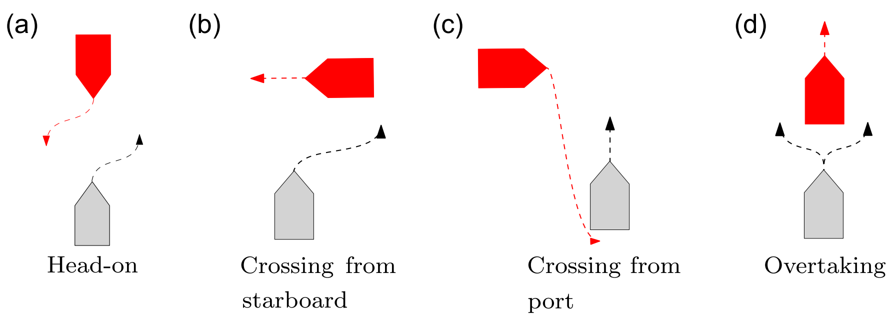


FIGURE 1 COLREGs scenarios and actions for two power-driven vessels. The scenarios are described from the gray (bottom) vessel's perspective. (a) Head-on, (b) crossing from starboard, (c) crossing from port, and (d) overtaking. COLREGs, International Regulations for Preventing Collisions at Sea [Color figure can be viewed at wileyonlinelibrary.com]

situation is such that collision cannot be avoided by the action of the give-way vessel alone (cf., Rules 8(f.ii) and 17(b)).

The above statements from COLREGs illustrate that some scenarios are straightforward to interpret (cf., Figure 1) whereas others are complex. Complex scenarios can easily arise involving one or more obstacle vessels. For a single obstacle, a complex situation may arise at the boundary between two basic scenarios, especially when it becomes unclear which vessel is the give-way or stand-on vessel. To avoid such challenging scenarios, COLREGs requires a vessel that is the give-way vessel in a particular scenario to refrain from actions that result in switching between scenarios. A specific case is found in Rule 13 for overtaking, which states that "*any subsequent alteration of the bearing between the two vessels shall not make the overtaking vessel a crossing vessel within the meaning of these Rules or relieve her of the duty of keeping clear of the overtaken vessel until she is finally past and clear*."

In general, the situation becomes complex when the behavior of the vessels involved becomes unpredictable. Unpredictable behaviors are even more challenging in multi-obstacle scenarios where some vessels obey the rules and others do not. We will present (in Section 5) both basic and complex scenarios from the sea trials that verify COLREGs-compliance in both single- and multi-obstacle encounters.

3 | SYSTEM ARCHITECTURE FOR AUTONOMY AND REMOTE CONTROL

3.1 | Autonomous vessel

The ASV is Maritime Robotics' research and development vessel called Telemetron (shown in Figure 2a). Telemetron is a Polar Circle 845 Sport vessel, which is a stable and highly maneuverable Rigid Buoyancy Boat (RBB). It is type-approved as a class C vessel, and hence has an operational limitation of

- wind speed up to 13.8 m/s,
- wave height up to 2 m.

Some relevant specifications are shown in Table 1.

TABLE 1 ASV Telemetron specifications

Length	8.45 m
Width	2.71 m
Weight	1,675 kg
Maximum speed	34 kn
Power	225 hp
Propulsion	Yamaha outboard engine
Engine control	Electromechanical actuation of throttle
Rudder control	Hydraulic actuation of engine angle

Abbreviation: AIS, automatic identification system.

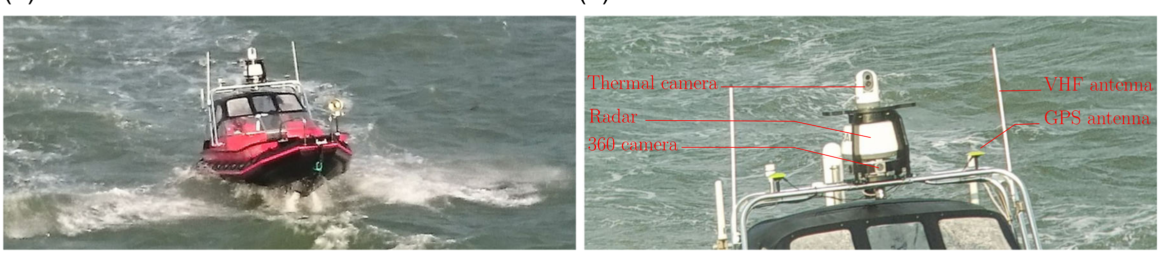
The ASV is equipped with several hardware and software components that make both remote control and autonomous navigation possible. The imaging sensors used for situational awareness and remote operation of the ASV during the sea trials can be seen in Figure 2b. Details of the sensor system and control architecture are presented next.

3.2 | ASV system architecture

Figure 3 shows the setup for the verification exercise in the North Sea and the vessels officially involved. We installed Maritime Robotics' remote vehicle control station (VCS) on the bridge of the Netherlands Coastguard vessel, Zirfaea, and we used the point-to-point maritime broadband radio (MBR) from Kongsberg Seatex and Maritime Robotics' Owl (MR-Owl) very high frequency radio equipment for safe and reliable communication with the ASV.

The VCS on the bridge of Zirfaea is part of the control system architecture shown in Figure 4. The VCS computer runs a graphical user interface for remote control and situational awareness. To enhance the operator's situational awareness, the VCS displays an electronic nautical chart (ENC), overlaid by a radar image, and it presents a 360° camera coverage of the ASV's surroundings. The radar system installed on the ASV is a Simrad Broadband 4G^{TM} (Navico Holding AS, Egersund, Norway) radar, and the camera rack includes an MR custom-made 360 camera

(a) (b)



ASV Telemetron — Imaging and communication sensors

FIGURE 2 The polar circle 845 vessel (Telemetron) in the North Sea. (a) ASV Telemetron and (b) imaging and communication sensors. ASV, autonomous surface vehicle [Color figure can be viewed at wileyonlinelibrary.com]

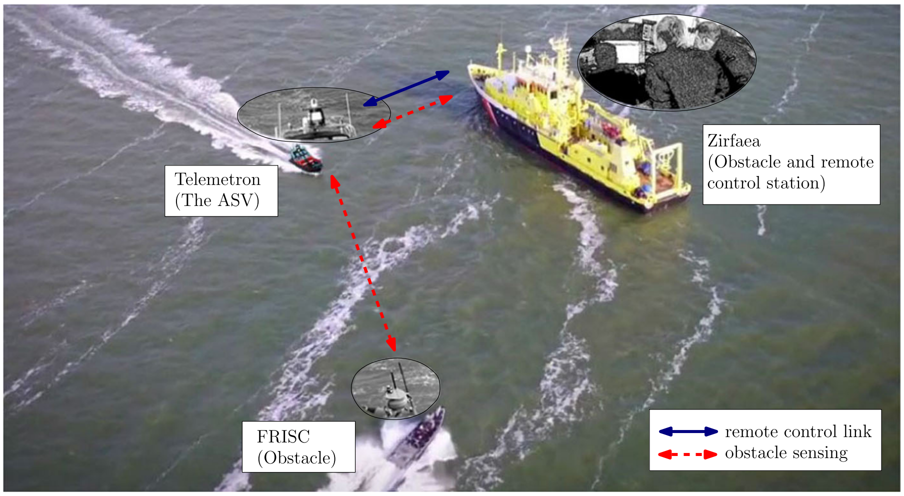


FIGURE 3 Vessels officially involved in the sea trials, and the communication architecture used. ASV, autonomous surface vehicle; FRISC, Fast Raiding, Interception and Special forces Craft [Color figure can be viewed at wileyonlinelibrary.com]

system and an forward-looking infrared (FLIR) thermal camera (see Figure 2b). Collision avoidance aiding is also provided at the VCS by displaying information about obstacles and the time (TCPA) to the closest point of approach (CPA) to other vessels in the ASV's vicinity. The situational awareness and collision avoidance information displayed at the VCS is obtained from the ASV's on-board system (OBS), illustrated in Figure 4, which consists of subsystems for obstacle tracking, collision avoidance, guidance, navigation, and vehicle control.

We used the automatic identification system (AIS) for obstacle motion sensing and tracking for autonomous collision avoidance decision making. Although obstacle tracking using AIS has reliability issues and depends on the accuracy of the obstacle vessel's global positioning system (GPS) and navigation system, it is sufficient for the sea trials because our main focus is on the behavior of the ASV in different challenging COLREGs scenarios.

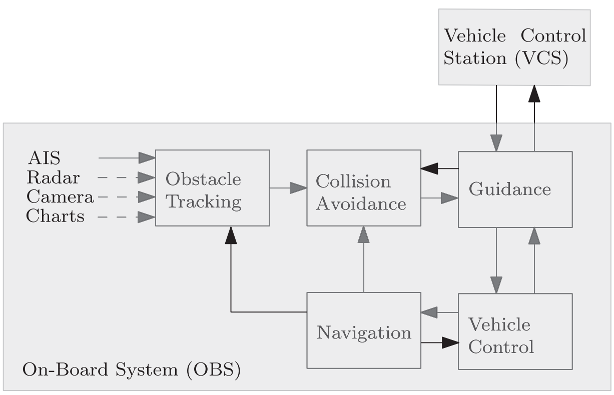


FIGURE 4 The ASV's control system architecture, showing the main components of the OBS, remote link to the VCS, and the flow of information (cf., Figure 3). In this setup, only AIS obstacles are considered in the autonomous decision-making process. Information about radar, camera, and mapped obstacles is made available at the VCS to aid remote control decisions. AIS, automatic identification system; ASV, autonomous surface vehicle; OBS, on-board system; VCS, vehicle control station

Refer to Kufoalor et al. (2019) for later extensions to radar-based tracking.

3.3 | Obstacle vessels

For collision avoidance scenarios involving a single dynamic obstacle, the Fast Raiding, Interception and Special forces Craft (FRISC®) of the Royal Netherlands Navy was used. The FRISC vessel can be seen in Figure 3. The Coastguard's Zirfaea was also included in multi-obstacle scenarios, and all vessels of opportunity with AIS that entered the test area were considered as dynamic obstacles in the autonomous decision process.

4 | COLLISION AVOIDANCE STRATEGY

4.1 | MPC-based COLREGs-compliant collision avoidance method

We used the scenario-based MPC collision avoidance method proposed in Johansen et al. (2016) and the implementation of Hagen et al. (2018) for COLREGs-compliant decision making. The MPC approach evaluates a cost function for a finite set of ASV control behaviors and selects the control behavior that yields the minimum cost over the entire prediction horizon, considering all nearby obstacles and the ASV's motion constraints. Specifically, the method solves the following optimization problem:

$$k^*(t_0) = \arg\min_k \mathcal{H}^k(t_0), \tag{1}$$

where

$$\mathcal{H}^k(t_0) = \max_i \max_{t\in\mathcal{D}(t_0)} \left(c_{i,t}(u_m^k,\chi_m^k) + \mu_{i,t}(u_m^k,\chi_m^k) + \tau_{i,t}(u_m^k,\chi_m^k)\right) + f(u_m^k,\chi_m^k) + g(u_m^k,\chi_m^k),$$

using the set $\mathcal{D}(t_0) = \{t_0, t_0 + T_s, ..., t_0 + T\}$, where t_0 is the current time, T_s is the sampling time, and T is the prediction horizon.

We provide a brief description of the cost function components $c_{i,t}, \mu_{i,t}, \tau_{i,t}, f, g$ in this section, and we refer to Hagen et al. (2018) and Johansen et al. (2016) for their detailed specifications.

Essentially, formulation (1) states that the optimal control behavior k^* in a dangerous situation is the control behavior k that results in the minimum worst-case hazard. The cost function $\mathcal{H}^k$ expresses the hazard associated with selecting a control behavior k defined by course (χ_m^k) and speed (u_m^k) modifications that are applied to corresponding desired reference values, χ_d, u_d, for the course (χ) and speed (u), respectively. We use the following set of alternative control behaviors, which we assume to be fixed on the prediction horizon:

- course offset in degrees: $\chi_m^k \in \{-90, -75, -60, -45, -30, -15, 0, 15, 30, 45, 60, 75, 90\}$;
- speed factor: $u_m^k \in \{1, 0.5, 0\}$, which translates to 'keep speed', 'slow down', or 'stop'.

We use a minimum of 15° course offset to ensure that a change in course by the ASV is clear and readily apparent to other vessels observing visually or by radar (cf., Rule 8b of COLREGs). The use of speed factors, instead of fixed speed offsets, ensures that changes in speed are larger for high vessel speeds than that for low speeds. We also avoid increasing speed beyond the desired reference speed in dangerous situations.

The function $c_{i,t}$ in (1) denotes the cost of colliding with obstacle i at time t, considering a collision risk that depends on the time and distance to the CPA and scales with the relative velocity ($\mathbf{v}_t^k - \mathbf{v}_{i,t}^k$) of the ASV and obstacle i:

$$c_{i,t} = \begin{cases} K_i^{\text{coll}} \left\| \mathbf{v}_t^k - \mathbf{v}_{i,t}^k \right\|^2 \dfrac{1}{|t - t_0|^p} \left(\dfrac{d_i^{\min}}{d_{i,t}^k} \right)^q & \text{if } d_{i,t}^k \le d_i^{\min}, \\ 0 & \text{otherwise}. \end{cases} \tag{2}$$

The allowed CPA (i.e., $d_i^{\min}$) is defined by a safety distance parameter (d^{safe}) and the obstacle's length (L_i). Specifically, $d_i^{\min} = d^{\text{safe}} + L_i/2$ is used to define the radius of a circular safety region, which encloses obstacle i.

In (2), t_0 is the current time and $t > t_0$ is the time in the prediction horizon. The distance $d_{i,t}^k$ is the predicted distance between the ASV and obstacle i at time t for control behavior k. The exponent $q \ge 1$, and $p \ge 0.5$ weighs the time until collision and prioritizes obstacles close in time over those that are more distant. The collision factor K_i^{coll} allows different weights to be assigned to different obstacles depending on obstacle type and size.

The function $\mu_{i,t}$ in (1) expresses the cost of violating COLREGs with respect to obstacle i at time t. It consists of binary indicators that indicate when a logic expression for a particular rule is true or false. For example, Rule 14 of COLREGs is violated in a head-on situation when obstacle i is close (defined by a parameter d^{close}) and on the ASV's starboard side. To avoid unnecessary switching of control behaviors, a transitional cost, $\tau_{i,t}$, is used to penalize the termination of COLREGs-compliant maneuvers. The transitional cost also consists of binary indicators that take on the value 1 when an alternative control behavior k leads to a change in the side an obstacle is supposed pass.

The cost of maneuvering effort is specified by the function f, which penalizes deviations from the desired reference values, χ_d, u_d, and the last commanded control behavior. The function g in (1) is a grounding cost that penalizes control behaviors that will result in collision with land or defined *no-go* zones.

The cost for each control behavior k at time $t \in \mathcal{D}(t_0)$ is calculated based on the predicted state of the ASV and each obstacle i, obtained from the simulation of their trajectories. The fast dynamics of the ASV allows us to use the following simple kinematic model for predicting the ASV's future motion:

$$\dot{\eta} = R(\chi)v, \tag{3}$$

where $\eta = (x, y, \chi)$ denotes the position and course in the earth-fixed frame, $v = (v_x, v_y, r)$ represents the velocities in surge, sway, and yaw specified in the body-fixed frame, and $R(\chi)$ is a rotation matrix from body-fixed to earth-fixed frame. The trajectory prediction is achieved by inserting the modifications (u_m^k, χ_m^k) for each scenario k into (3), that is, $v = (v_x = u_d \cdot u_m^k,\ v_y = 0,\ r = 0)$ and $R(\chi = \chi_d + \chi_m^k)$. This prediction approach assumes that the time to change the ASV's speed or course is negligible, and that the ASV's motion controllers are able to compensate for vessel-model mismatch and environmental disturbances due to wind and ocean current. The same model (3) is used for predicting the trajectory of each obstacle i, using the latest position and velocity measurements available at each sampling time. This results in a straight-line prediction of the obstacles' motion.

The computational steps involved in the MPC strategy described above are summarized in Algorithm 1. We use a receding horizon implementation, which implies that Algorithm 1 is repeated at regular intervals to account for new sensor information. For the verification exercise, we recomputed an optimal solution every 5 s. Note that the solution method outlined in Algorithm 1 allows the use of more sophisticated prediction models and a straightforward implementation of robustness enhancing extensions in the form of weather scenarios and extra obstacle scenarios as proposed in Johansen et al. (2016) and Kufoalor et al. (2019). Moreover, by using a deterministic optimization strategy and avoiding the use of a numerical solver, we can guarantee convergence of the algorithm for a predefined number of cost function evaluations.

Algorithm 1 Scenario-based MPC strategy for maritime collision avoidance

1: Update the ASV state using measurements from the navigation system (see Fig. 4)
2: Obtain a list of obstacles and their estimated state from the tracking system (see Fig. 4)
3: **for** each obstacle i **do**
4: Compute the current COLREGs scenario (i.e. at time $t = 0$, assuming $t_0 = 0$)
5: Compute the predicted state at each time $t \in \{T_s, 2T_s, \ldots, T\}$ using (3) { Note that a more sophisticated prediction model can be used instead of (3) }
6: **end for**
7: $\mathcal{H}^k_{\min} \leftarrow \infty$ { initial value for the minimum worst-case hazard }
8: **for** each ASV control behavior k, i.e. (u^k_m, χ^k_m) **do**
9: Compute the predicted ASV state at each time $t \in \{T_s, 2T_s, \ldots, T\}$, using (3) with $v = (v_x = u_d \cdot u^k_m,\ v_y = 0,\ r = 0)$ and $R(\chi = \chi_d + \chi^k_m)$ { a more accurate model can be used instead of (3) }
10: $\mathcal{H}^k_{i,\max} \leftarrow 0$ { initial value for the worst-case hazard for all obstacles }
11: **for** each obstacle i **do**
12: $\mathcal{H}^k_{i,t,\max} \leftarrow 0$ { initial value for the worst-case hazard for obstacle i $\forall t \in \{0, T_s, 2T_s, \ldots, T\}$ }
13: **for** each $t \in \{0, T_s, 2T_s, \ldots, T\}$ **do**
14: Compute the predicted hazard $\mathcal{H}^k_{i,t}$ given by the sum of $c^k_{i,t}$ (collision cost), $\mu^k_{i,t}$ (COLREGs cost), and $\tau^k_{i,t}$ (transitional cost, if scenario at $t > 0$ differs from scenario at $t = 0$, cf. line 4)
15: **if** $\mathcal{H}^k_{i,t} > \mathcal{H}^k_{i,t,\max}$ **then**
16: $\mathcal{H}^k_{i,t,\max} \leftarrow \mathcal{H}^k_{i,t}$ { worst-case hazard after considering obstacle i at time t }
17: **end if**
18: **end for**
19: **if** $\mathcal{H}^k_{i,t,\max} > \mathcal{H}^k_{i,\max}$ **then**
20: $\mathcal{H}^k_{i,\max} \leftarrow \mathcal{H}^k_{i,t,\max}$ { worst-case hazard after considering obstacle i }
21: **end if**
22: **end for**
23: Compute the predicted hazard $\mathcal{H}^k = \mathcal{H}^k_{i,\max} + f^k + g^k$ { cf. $\mathcal{H}^k$ in (1) }
24: **if** $\mathcal{H}^k < \mathcal{H}^k_{\min}$ **then**
25: $\mathcal{H}^k_{\min} \leftarrow \mathcal{H}^k$ { minimum worst-case hazard after considering control behavior k }
26: $u^{k^*}_m \leftarrow u^k_m,\ \chi^{k^*}_m \leftarrow \chi^k_m$
27: **end if**
28: **end for**
29: **return** $(u^{k^*}_m,\ \chi^{k^*}_m)$

4.2 | Inherent properties and robustness

The MPC collision avoidance method described above prioritizes straight-line motion, which is considered as predictable behavior in a maritime environment. The strategy is to seek the least conservative solution according to the given constraints. This is achieved by prioritizing solutions that result in a tangential motion with respect to the boundary of the projected combined safety region associated with the obstacle vessels.

Due to the implementation of a COLREGs transitional cost $\tau_{i,t}(\cdot)$, it is straightforward to prioritize COLREGs-compliant maneuvers in long-range encounters. Moreover, using a collision cost $c_{i,t}(\cdot)$ that scales with the collision time, range, and relative velocity (cf., (2)), ensures that the MPC strategy will choose an evasive maneuver if collision becomes imminent.

Another important property of the MPC strategy is its inherent robustness to noise or uncertainty. All potentially uncertain variables that affect the collision avoidance decisions are evaluated in the cost function $\mathcal{H}^k$ over a long prediction horizon T. In combination with an appropriate choice of sampling time T_s and a scenario grid of alternative control behaviors, the cost function provides a filtering effect that ensures that changes in each variable must be significant enough to produce a change in the decisions. Moreover, the collision cost $c_{i,t}(\cdot)$ defined in (2) prioritizes avoiding collision hazards that are close in time over those that are more distant and usually more uncertain (Johansen et al., 2016).

4.3 | Practical aspects: tuning and operational modes

The MPC-based collision avoidance system is a simplification of the more general method presented in Johansen et al. (2016). The method depends on several parameters that must be selected carefully to achieve the desired ASV behavior in different scenarios. For instance, we have specified a larger set of alternative modifications for the ASV's course χ^k_m than that for speed u^k_m (see Section 4.1), and we tuned the cost function in (1) to prioritize course changes over speed. This ensures that the actions of the ASV in a dangerous situation are clear and easy to observe by other vessels, especially those operated by humans (cf., COLREGs Rule 8).

By implementing a COLREGs transitional cost (Hagen et al., 2018), we avoid the implementation of a specific guidance law in the prediction model of the MPC. We assume that the desired reference values from the guidance system remain constant over the prediction horizon, and we depend on the transitional cost to avoid unnecessary switching of control behavior due to discrepancies between the actual guidance dynamics and the constant model. An alternative approach is to implement a model-switching strategy for each guidance strategy installed on the ASV, for example, line-of-sight (LOS) path following, pure pursuit (waypoint target), or course-/heading-hold control.

Furthermore, it may be necessary to adapt the COLREGs-compliant decision parameters, such as the minimum CPA or safety distance (d^{safe}), decision initiation distance (d^{init}), COLREGs-scenario evaluation distance (d^{close}), prediction horizon (T), sampling time (T_s), and the various weights that determine the priority of the components of the cost function (cf., Johansen et al., 2016). Since it is difficult (if not impossible) to use a single set of parameters to capture the unique nature of all scenarios, we propose to use different sets of parameters for different operational modes of the ASV. For example,

- open sea mode,
- near coast mode,
- narrow channel mode,
- harbor mode,
- mission-specific mode.

The appropriate mode can be selected by either an operator or automatically based on the ASV's environment/location and operational status. At sea, it is natural to use larger parameter values for the various distances and prediction horizon, compared with near coast or harbor modes. Some channels may be narrow or governed by traffic separation schemes, requiring appropriate adaptations of the ASV's behavior, while a specific ASV mission/operation may require a particular collision avoidance behavior. An example is the case where the ASV is supposed to follow a preplanned pattern for survey purposes, similar to the expectations of the proposed autonomous water monitoring program for the Dutch North Sea (see Section 1). In this case, it may be desirable to reduce the allowed offset limit from the planned path and prioritize the use of speed modifications for collision avoidance. Although the collision avoidance system was tuned for open sea and near coast modes, only the near coast mode was verified during the sea trials presented in this paper.

5 | VERIFICATION EXERCISE AND RESULTS

5.1 | Location and environmental conditions

To demonstrate that the ASV is capable of navigating autonomously in the Dutch waters of the North Sea, a test location (400 km^2) to the west of Texel, in the Netherlands, was assigned by the Department of Maritime Affairs, Coastguard, and the Traffic Control Center in Den Helder. This test location is a relatively low-traffic area, where large sea-room is available for collision avoidance maneuvers, and therefore allowing the "Open sea mode" parameterization of the collision avoidance system to be used. Considering the size and maneuvering capabilities of the vessels involved in the sea trials, a safety distance (d^{safe}) of 0.2 nautical mile (NM) and a COLREGs-compliant decision initiation distance (d^{init}) of 4 NM was required.

However, due to extreme weather conditions (with wind speeds of 10–28 m/s) in the assigned test area, the test location was moved from the west side of Texel to the east side in the Wadden Sea. Extracts from detailed weather forecast reports from Day 2 of the test week can be seen in Figure 5. Note that the weather conditions in the Wadden Sea were still rough enough to challenge the certified limits of the ASV Telemetron, which can operate in sea states of up to 2 m wave heights (i.e., the light green zone in Figure 5a) and 13.8 m/s wind speeds (i.e., max 6 on the beaufort scale in Figure 5b). The new test area is also closer to shore, with more traffic and limited sea-room for collision avoidance maneuvers. Therefore, we used a set of parameters for the "Near coast mode" with a reduced safety distance of 0.1 NM and a COLREGs-compliant decision distance of 1 NM. The same set of parameters was used for all the test scenarios.

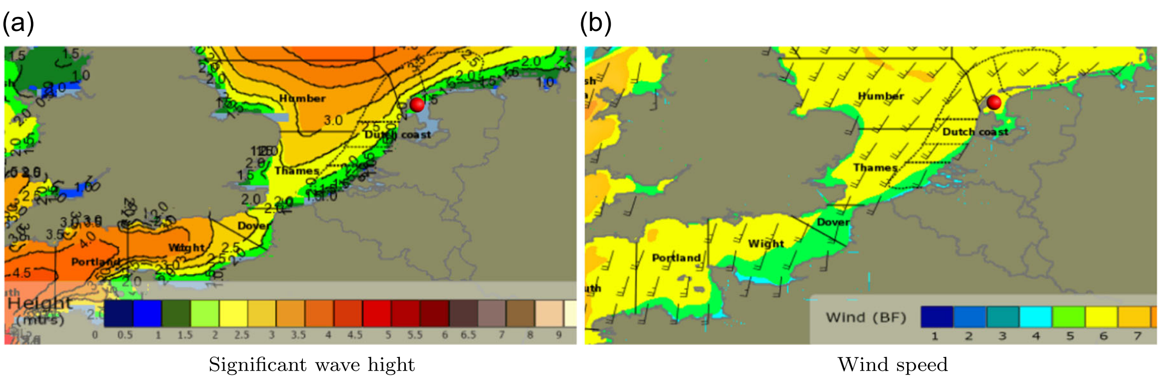


FIGURE 5 Meteorological data of the North Sea on November 21, 2017. The sea trials were performed in the area indicated by the symbol ●, close to the Dutch coast. (a) Significant wave height and (b) wind speed [Color figure can be viewed at wileyonlinelibrary.com]

5.2 | Test scenarios

Different challenging scenarios that verify compliance with the applicable rules of COLREGs discussed in Section 2 are presented in this section. The scenarios were set up using remote commands supervised by two LTZ 2 of the Royal Netherlands Navy at the VCS on the Coastguard vessel Zirfaea (see Figure 3). The Navy's assessment of each test scenario can be found in Verheul (2017, Appendix G), and we use the same title given to some scenarios during the verification exercise. Due to the weather conditions and long distances considered during the trials, it was not possible to rely on lookout from Zirfaea for remote control and monitoring of most scenarios. Reliability of the VCS was therefore a crucial factor in the verification process.

A screenshot from the VCS computer is shown in Figure 6, where relevant information about the ASV's motion, obstacles, and collision danger are highlighted. The vessels officially involved in the sea trials, with boxed labels in Figure 6, were given planned routes at the beginning of each scenario, whereas the other vessels seen at the VCS entered/exited scenarios at will, providing different interesting and spontaneous collision avoidance situations for the ASV. As an introduction to the dynamic nature of the test scenarios and the performance of the ASV, we will start with a brief description of the first test, which is captured in Figure 6.

The multi-obstacle scenario in Figure 6 started with the ASV traveling at 10 kn on the brown straight-line path parallel to the coast line. The ASV had to first avoid colliding with the FRISC, which was crossing from the ASV's starboard along the blue highlighted path. The scenario developed quickly into a crossing and head-on situation with another vessel, ELSE JEANNETTE, which entered the test area unannounced. The COLREGs-compliant behavior of the ASV can be seen by its trail shown in green. The ASV prioritized COLREGs-compliance, especially predictability, instead of attempting to steer towards its original path. At the current position of the vessels shown in the VCS, the FRISC accelerated to 40.7 kn (see AIS object information in Figure 6) creating a dangerous situation predicted ahead of the ASV and involving ELSE JEANNETTE, which was close by. Nevertheless, the highly uncertain behavior of the FRISC did not lead to unpredictable course changes by the ASV.

We will take a closer look at the vehicle speed, course, position trajectories, and control variables in the scenarios presented next.

5.3 | Crossing scenarios

In Figure 6, we saw a crossing scenario where the ASV was the give-way vessel and therefore took full responsibility in avoiding collision. Figure 7 shows another crossing scenario that tests the ASV's ability

FIGURE 6 Vehicle control station (VCS) view showing information about the ASV (green bottom zoom window), obstacle vessel (blue upper right zoom window), and collision danger (red upper left zoom window). A prediction of the potential collision point between the ASV and FRISC is indicated with a red projection symbol, and a yellow projection indicates the CPA to another danger ahead. The large red arc is part of a circular collision avoidance region (of radius 1 NM) specified around the ASV. Obstacle vessels outside this region are not considered in the ASV's autonomous decision process. The solid blue and brown lines are planned paths tracked by the ASV (Telemetron), FRISC, or ZIRFAEA in different scenarios. ASV, autonomous surface vehicle; CPA, closest point of approach; FRISC, Fast Raiding, Interception and Special forces Craft [Color figure can be viewed at wileyonlinelibrary.com]

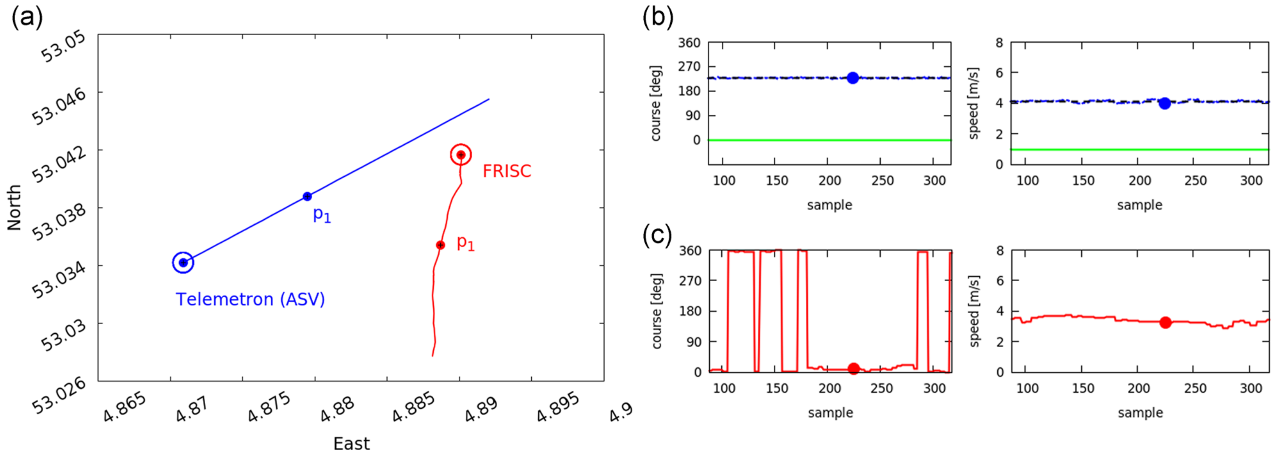


FIGURE 7 Law-abiding obstacle scenario. Crossing scenario where the obstacle vessel FRISC gives way and the ASV stands on according to COLREGs. (a) Position trajectories. The end of each trajectory is indicated by the symbol ⊙, and the vessels' positions at the same sampling time are indicated by p_1. The position of the obstacle vessel FRISC is enclosed by a relatively large circular safety region. (b) ASV course χ and speed u. Desired values, χ_d and u_d, from LOS guidance (– – –), course offset χ_m^{k*} and speed factor u_m^{k*} from MPC (——), and measurements (—·—). The points indicate the course and speed at p_1 in (a). (c) Obstacle course and speed. ASV, autonomous surface vehicle; COLREGs, International Regulations for Preventing Collisions at Sea; FRISC, Fast Raiding, Interception and Special forces Craft; LOS, line-of-sight; MPC, model predictive control [Color figure can be viewed at wileyonlinelibrary.com]

to understand its responsibility as a stand-on vessel. During the crossing scenario, the course and speed of FRISC indicated clearly that it will cross behind the ASV. The ASV therefore stayed on its path according to COLREGs (cf., Rules 15 and 17(a.i)). In Figure 7a, the end of the position trajectories is indicated by a circle. The vessels were 680 m apart at the CPA labeled p_1, and the corresponding course and speed values for the ASV and obstacle can be seen in Figure 7b,c. Note that the MPC collision avoidance decision produced throughout this scenario was a course offset $\chi_m^{k*} = 0$, which means "keep course", and a speed factor $u_m^{k*} = 1$, which means "keep speed" (cf., alternative control behaviors in Section 4.1).

5.4 | Overtaking scenarios

Figure 8 shows dynamic scenarios involving the ASV Telemetron, the Navy vessel FRISC, the passenger vessel RIVAL, and the fishing vessel TH4 ELIZABETH. Both RIVAL and TH4 ELIZABETH were not officially part of the trials, but they were considered in the ASV's decisions. The ASV was commanded to keep a speed of 20 kn (~10 m/s) to test the case where the ASV overtakes the FRISC, which was traveling on the same path at a speed of approximately 5 kn (~2.5 m/s, cf., speed curves in Figure 8c,d). RIVAL entered the scenario at an early stage, traveling in the opposite direction (cf., p_1 in Figure 8a and the corresponding scenario description in Figure 8b). Although the ASV was overtaking FRISC, RIVAL made about a 90° course change creating a crossing scenario which the ASV had to consider in its collision risk evaluation. However, the sudden change of course towards the ASV did not cause any reactive maneuvers by the ASV because the best predicted behavior, considering COLREGs, is to stand on (see Rules 15 and 17(a.i)). RIVAL stopped shortly after the turn and did not interfere any longer with the overtaking scenario, which finished with the ASV almost 500 m ahead of FRISC at p_2 (see Figure 8a).

At p_2, the ASV's reference speed was changed to 10 kn (~5 m/s), and FRISC was ordered to speed up to 20 kn (~10 m/s) to test the case where the ASV is approached aggressively from behind. Considering the speed, closeness, and the collision course of the FRISC, the ASV quickly steered off the path with a predictable behavior to stay clear and avert the collision danger created by FRISC. The action of the ASV is in line with Rule 17(a.ii) of COLREGs (cf., discussion in Section 2.2).

The movement of TH4 ELIZABETH can be seen in Figure 8a, from point p_2. Although TH4 ELIZABETH approached in a crossing scenario, and may therefore expect a stand-on behavior by both the ASV and FRISC, the risk of collision with FRISC was much higher for the ASV. Moreover, choosing a clear starboard maneuver, instead of a course change towards port or speed reduction, is reasonable in this situation. Note that the ASV returned to its original path after crossing ahead of TH4 ELIZABETH, with a distance of more than 1,000 m between the two vessels.

5.5 | Combined overtaking and crossing scenarios

The results in Figure 9 were obtained from a complex scenario where the ASV had to overtake ZIRFAEA while keeping well clear of FRISC, which was crossing the paths of both ZIRFAEA and the ASV. FRISC was not complying with COLREGs, and it had slight course changes which made its intention more uncertain the closer the vessels came to each other. Again, the ASV prioritized predictability according to COLREGs, and it avoided reactive course changes to reduce the risk of collision. At $p1$ in Figure 9a, FRISC appeared to be crossing ahead of both ZIRFAEA and the ASV, although it was required to cross behind according to COLREGs. Note that the ASV maintains almost a

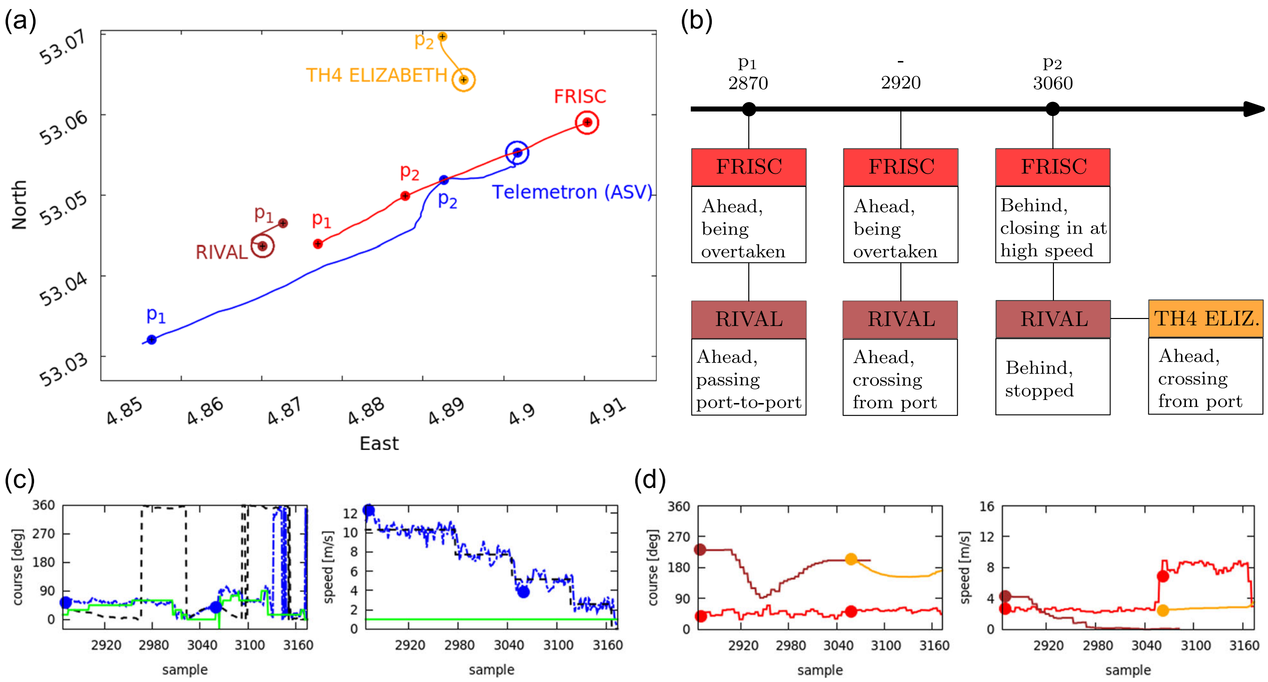


FIGURE 8 Overtaking scenarios in a multi-obstacle environment. The ASV overtakes obstacle vessel FRISC while dealing with interactions from another obstacle, RIVAL. FRISC later closes in on the ASV from behind while the vessel TH4 ELIZABETH approaches from the ASV's port side. (a) Position trajectories. The end of each trajectory is indicated by the symbol ⊙, and the vessels' positions at the same sampling time are indicated by p_1 and p_2. The position of each obstacle is enclosed by a relatively large circular safety region. (b) Timeline of identified COLREGs situation for each obstacle vessel considered by the ASV. Compare scenarios at p_1 and p_2 with indications in (a). (c) ASV course χ and speed u. Desired values, χ_d and u_d, from LOS guidance (– – –) , course offset $\chi_m^{k^*}$ and speed factor $u_m^{k^*}$ from MPC (——), and measurements (—·—). The points indicate the course and speed at p_1 and p_2 in (a). (d) Obstacle course and speed. ASV, autonomous surface vehicle; COLREGs, International Regulations for Preventing Collisions at Sea; FRISC, Fast Raiding, Interception and Special forces Craft; LOS, line-of-sight; MPC, model predictive control [Color figure can be viewed at wileyonlinelibrary.com]

straight path until point p_1. The ASV's choice of behavior makes its intention and motion predictable to both ZIRFAEA and FRISC.

As the crossing and overtaking situation evolved between points p_1 and p_2 (see Figure 9a), the ASV had to explore the space between ZIRFAEA and FRISC by keeping a safe distance (at least 0.1 NM) and acting predictably according to COLREGs. Note that the ASV has passed between ZIRFAEA and FRISC at p_2. After point p_2, the ASV was steering gradually back to its original path when FRISC decided to approach ZIRFAEA. The approach speed and motion of FRISC (see Figure 9d) was associated with a high risk of collision in the ASV's decision method, and the ASV had to steer away briefly before returning to its original path when FRISC slowed down.

5.6 | COLREGs-decision boundary test scenarios

We will now examine the properties of the collision avoidance strategy of the ASV when the boundaries defining different COLREGs scenarios are challenged. More specifically, the following scenarios describe different situations where the obstacle vessel violates COLREGs by switching between overtaking and crossing scenarios (see [Rule 13]; IMO, 1972 and Section 2.2). During the verification exercise, we referred to the scenarios discussed next as "Navy pursuit evasion" and "Navy restriction" scenarios.

5.6.1 | Navy pursuit evasion scenario

In the test shown in Figure 10, FRISC approached the ASV from behind, targeting a bearing of 112.5°, which defines the boundary between the overtaking and crossing regions according to COLREGs. The ASV's speed was 8 kn (~4 m/s), whereas FRISC was traveling at 16 kn (~8 m/s, cf., speed curves in Figure 10b,c). At point p_1 in Figure 10a, the vessels are 600 m apart, and FRISC is in the ASV's overtaking region with a predicted trajectory passing in front of the ASV. Since the predicted CPA violates the ASV's desired safety distance, it steers towards port to create enough sea-room for FRISC to pass. Note that the ASV stands on for a while (for predictability according to COLREGs) before maneuvering at point p_1. After running almost parallel for about 2 min and reducing the separation distance to 500 m, FRISC made a rapid speed reduction to about 6 kn (~3 m/s seen in Figure 10c) and steered towards port. The action of FRISC changed the situation from an overtaking scenario to a crossing scenario. Since FRISC now appears to be crossing behind the ASV at a lower speed, the ASV steered towards its original path. However, FRISC returned to the overtaking region and started closing in on the ASV at 13 kn (~6.5 m/s). At point p_2 in Figure 10a, the distance between the two vessels is 250 m, and very close to the ASV's safety region. It can be seen in Figure 10 that the ASV's efforts towards the end of the scenario became purely evasive, but it still maintained a predictable behavior.

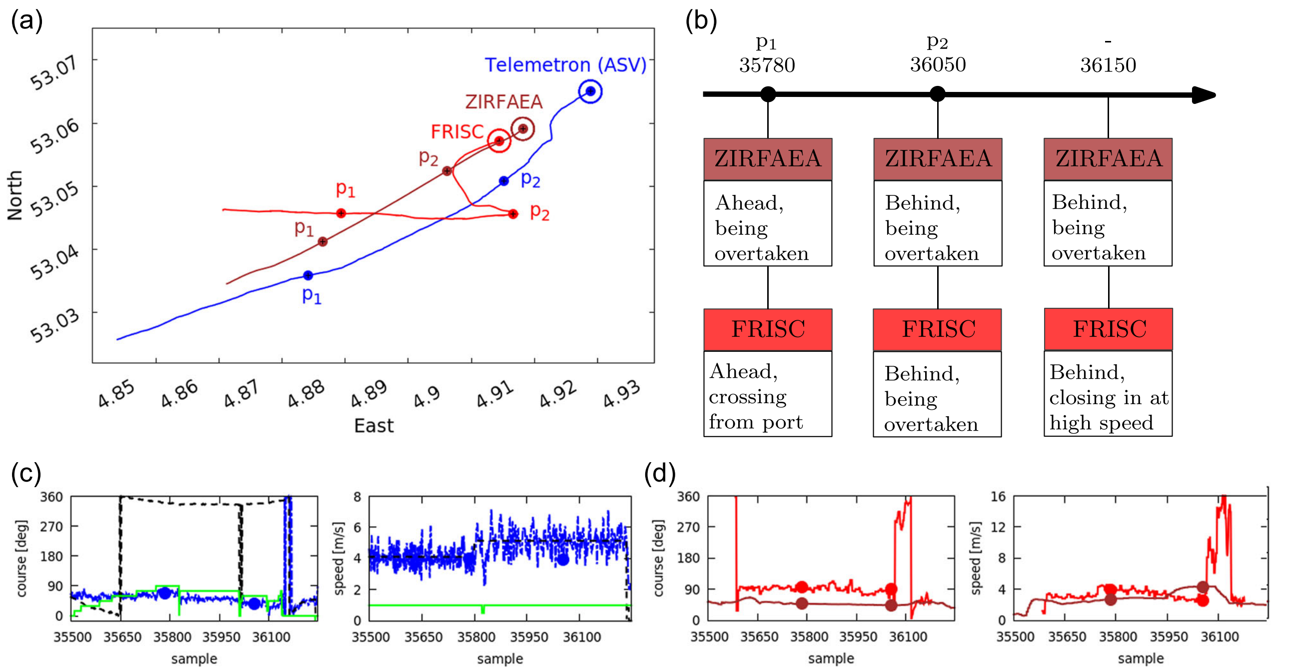


FIGURE 9 Emergency crossing and complex overtaking scenarios in a multi-obstacle environment. Obstacle vessel ZIRFAEA stands on according to COLREGs, whereas FRISC disregards COLREGs by crossing ahead from port. The ASV overtakes ZIRFAEA and explores the limited sea-room between FRISC and ZIRFAEA. (a) Position trajectories. The end of each trajectory is indicated by the symbol ⊙, and the vessels' positions at the same sampling time are indicated by p_1 and p_2. The position of each obstacle is enclosed by a relatively large circular safety region. (b) Timeline of identified COLREGs situation for each obstacle vessel considered by the ASV. Compare scenarios at p_1 and p_2 with indications in (a). (c) ASV course χ and speed u. Desired values, χ_d and u_d, from LOS guidance (– – –), course offset $\chi_m^{k^*}$ and speed factor $u_m^{k^*}$ from MPC (——), and measurements (—·—). The points indicate the course and speed at p_1 and p_2 in (a). ASV, autonomous surface vehicle; COLREGs, International Regulations for Preventing Collisions at Sea; FRISC, Fast Raiding, Interception and Special forces Craft; LOS, line-of-sight; MPC, model predictive control [Color figure can be viewed at wileyonlinelibrary.com]

5.6.2 | Navy restriction scenario

In contrast to the scenario described above, the next scenario shown in Figure 11 started with FRISC traveling ahead at 12 kn (~6 m/s seen in Figure 11c), and the ASV was crossing behind FRISC at a lower speed of 8 kn (~4 m/s in Figure 11b). FRISC kept its course almost constant throughout the scenario. However, FRISC was ordered to reduce its speed to 6 kn (~3 m/s) around point p_1 (see Figure 11c) when the ASV was just 300 m behind. Considering the 112.5° bearing boundary for overtaking and crossing from FRISC's perspective, the crossing scenario changed into an overtaking scenario. Although FRISC violated COLREGs at that moment, the ASV was obliged by COLREGs Rule 2 to take necessary actions to avoid collision. The ASV therefore made a clear and predictable starboard maneuver as seen between points p_1 and p_2 in Figure 11a,b. After point p_2, FRISC speed up again to 16 kn, and the ASV could steer towards its original path.

5.7 | Obstacle intention uncertainty scenarios

A challenging factor that affects the behavior of the ASV is the uncertainty of the future motion of dynamic obstacles. This is in general due to the unknown, and in some cases unpredictable, intention of other vessels. Figures 12 and 13 present results from different trials that verify the ASV's behavior in situations where the future motion of FRISC is uncertain.

A complex and uncertain situation is shown in Figure 12 with FRISC crossing from port and ZIRFAEA crossing from starboard. The ASV is the give-way vessel to ZIRFAEA and the stand-on vessel to FRISC. ZIRFAEA is a stand-on vessel to the ASV and a give-way vessel to FRISC, which must give way to both vessels. This scenario shows how complex the COLREGs-decision process can become when considering more than one obstacle. Depending on which distance and speed each vessel considers to be safe, and how each vessel assesses the situation, the outcome will vary.

In Figure 12, we see the case where FRISC enters an ongoing crossing situation between the ASV and ZIRFAEA (cf., point p_1 in Figure 12a). Both ZIRFAEA and the ASV were moving with 6 kn (~3 m/s), whereas FRISC accelerated to almost 20 kn (~10 m/s) when detected at p_1. The dangerous speed and course of FRISC makes its intention highly uncertain to the ASV. As a consequence, the ASV reacted by reducing speed and steering port. A desirable behavior is probably to continue steering starboard. However, the tuning of the MPC method allowed a purely evasive action to be selected by the ASV. Note that a straight-line prediction of the motion of FRISC suggests it will pass in front of the ASV and dangerously breach the required CPA distance, if FRISC does nothing about the situation. The reasoning behind the ASV's decision is to avert the dangerous situation by creating enough sea-room for FRISC to pass while still crossing behind ZIRFAEA.

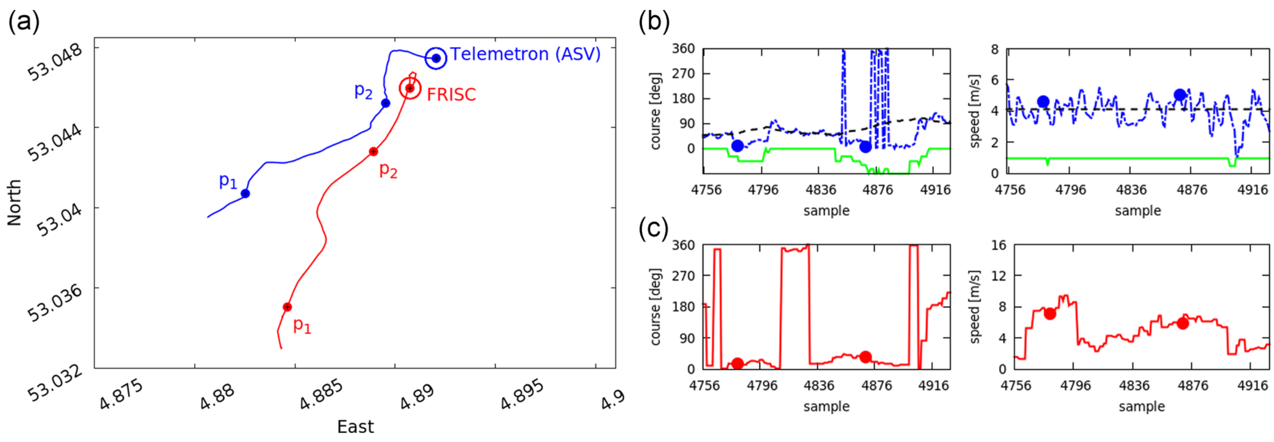


FIGURE 10 Navy pursuit evasion scenario. Obstacle vessel FRISC closes in on the ASV from behind and switches between overtaking and crossing scenarios. (a) Position trajectories. The end of each trajectory is indicated by the symbol ⊙, and the vessels' positions at the same sampling time are indicated by p_1 and p_2. The position of obstacle vessel FRISC is enclosed by a relatively large circular safety region. (b) ASV course χ and speed u. Desired values, χ_d and u_d, from LOS guidance (– – –), course offset χ_m^{k*} and speed factor u_m^{k*} from MPC (——), and measurements (–·–). The points indicate the course and speed at p_1 and p_2 in (a). (c) Obstacle course and speed. ASV, autonomous surface vehicle; FRISC, Fast Raiding, Interception and Special forces Craft; LOS, line-of-sight; MPC, model predictive control [Color figure can be viewed at wileyonlinelibrary.com]

Shortly after point p_1, FRISC reduced speed to 10 kn (~5 m/s in Figure 12d), and it can be seen in Figure 12a,d that FRISC maintained the uncertain course for, not complying with COLREGs, before making a clear course change to starboard. The new course and speed of FRISC allowed the ASV to find a more predictable and safer trajectory that crosses the path of both FRISC and ZIRFAEA.

5.7.1 | Navy versus Fisherman scenario

The last scenario shown in Figure 13 tests the case where unexpected actions of FRISC increase the risk of collision in a head-on situation. During the test, we referred to this scenario as "Navy versus Fisherman". The reason is that the behavior of the obstacle vessel FRISC mimics the behavior of some fishing vessels in the North Sea. The Navy's observation is that a fishing vessel may communicate its intention and later deviate from it. This leads to an unexpected situation that may be more dangerous than the case where no communication is made. The same situation occurs when the behavior of the obstacle vessel is clear enough to communicate an intention, and then the obstacle suddenly makes a significant change that contradicts the communicated intention.

The scenario in Figure 13 started with the ASV and FRISC approaching each other on a head-on collision course. The ASV steered early and clearly to starboard, and after a while FRISC also made a clear course change to starboard signaling its intention to cooperate by following COLREGs. However, at point p_1, FRISC makes a large course

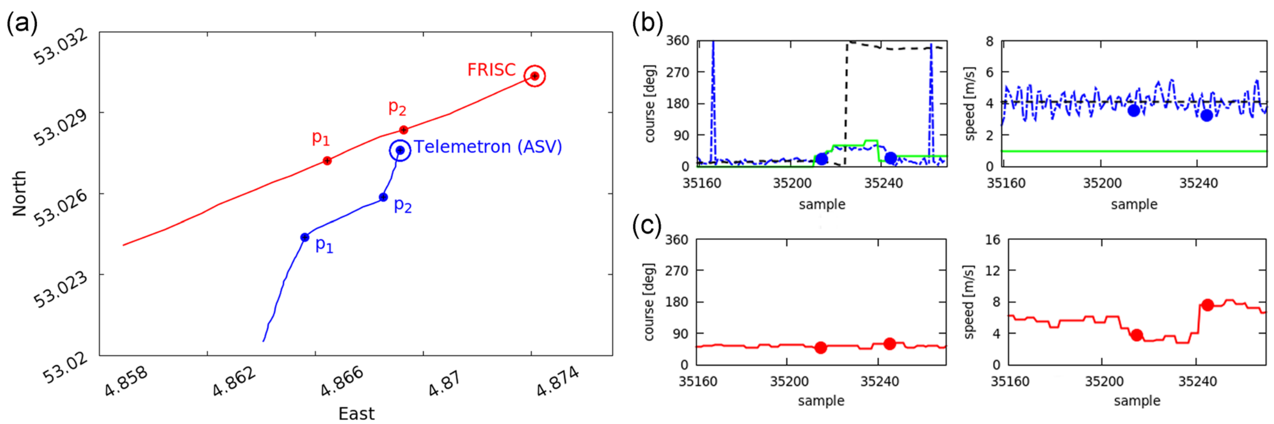


FIGURE 11 Navy restriction scenario. Obstacle vessel FRISC moves ahead and restricts the movement of the ASV by breaking and speeding, resulting in switches between overtaking and crossing scenarios. (a) Position trajectories. The end of each trajectory is indicated by the symbol ⊙, and the vessels' positions at the same sampling time are indicated by p_1 and p_2. The position of obstacle vessel FRISC is enclosed by a relatively large circular safety region. (b) ASV course χ and speed u. Desired values, χ_d and u_d, from LOS guidance (– – –), course offset χ_m^{k*} and speed factor u_m^{k*} from MPC (——), and measurements (–·–). The points indicate the course and speed at p_1 and p_2 in (a). (c) Obstacle course and speed. ASV, autonomous surface vehicle; FRISC, Fast Raiding, Interception and Special forces Craft; LOS, line-of-sight; MPC, model predictive control [Color figure can be viewed at wileyonlinelibrary.com]

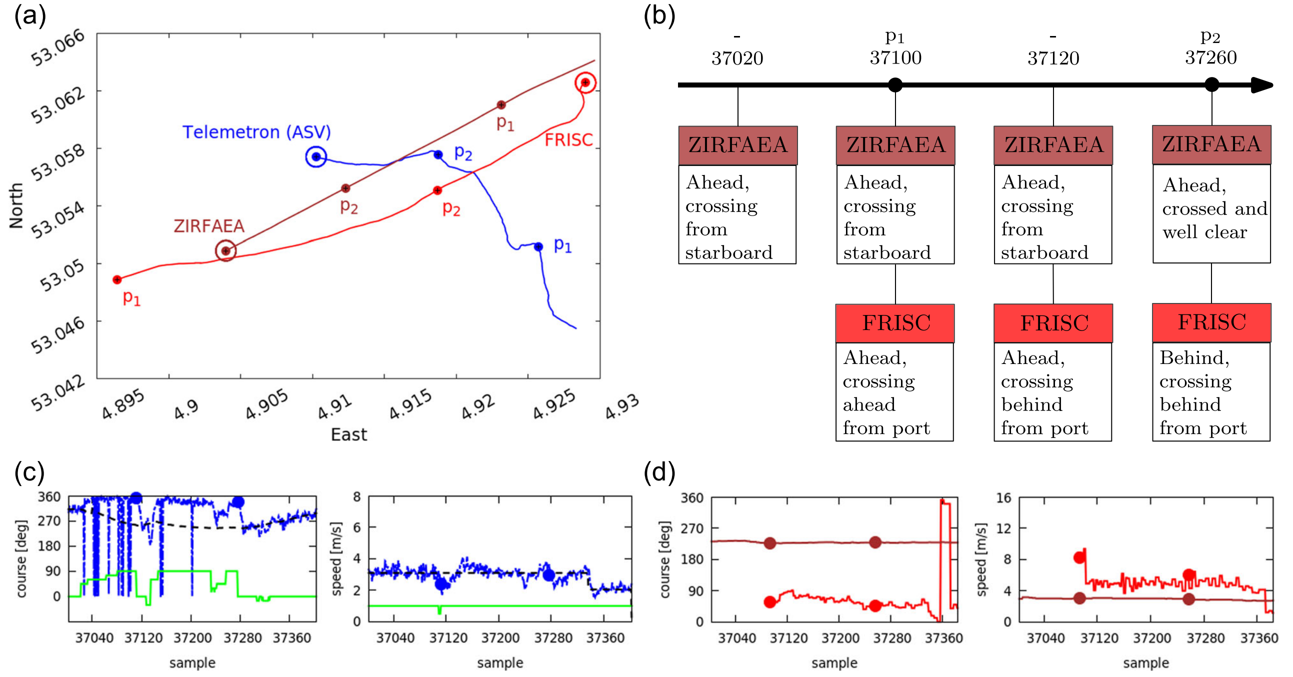


FIGURE 12 A complex crossing scenario in a multi-obstacle environment. The ASV's path is crossed by vessels from both port and starboard. Obstacle vessel FRISC switches its intention between crossing ahead and crossing behind. (a) Position trajectories. The end of each trajectory is indicated by the symbol ⊙, and the vessels' positions at the same sampling time are indicated by p_1 and p_2. The position of each obstacle is enclosed by a relatively large circular safety region. (b) Timeline of identified COLREGs situation for each obstacle vessel considered by the ASV. Compare scenarios at p_1 and p_2 with indications in (a). (c) ASV course χ and speed u. Desired values, χ_d and u_d, from LOS guidance (– – –), course offset χ_m^{k*} and speed factor u_m^{k*} from MPC (——), and measurements (–·–). The points indicate the course and speed at p_1 and p_2 in (a). (d) Obstacle course and speed. ASV, autonomous surface vehicle; COLREGs, International Regulations for Preventing Collisions at Sea; FRISC, Fast Raiding, Interception and Special forces Craft; LOS, line-of-sight; MPC, model predictive control [Color figure can be viewed at wileyonlinelibrary.com]

change of more than 90° towards the ASV's starboard, signaling the intention of leaving the path of the ASV. This means that the ASV could return to its path. At point p_1 (see Figure 13a), the vessels were more than 900 m apart, and FRISC's behavior did not pose a significant collision danger. Note that both vessels act predictably between points p_1 and p_2. The scenario changed again at point p_2 when FRISC decided to turn around, causing a close-range crossing situation where the vessels were only 600 m apart. The ASV reacted predictably from p_2

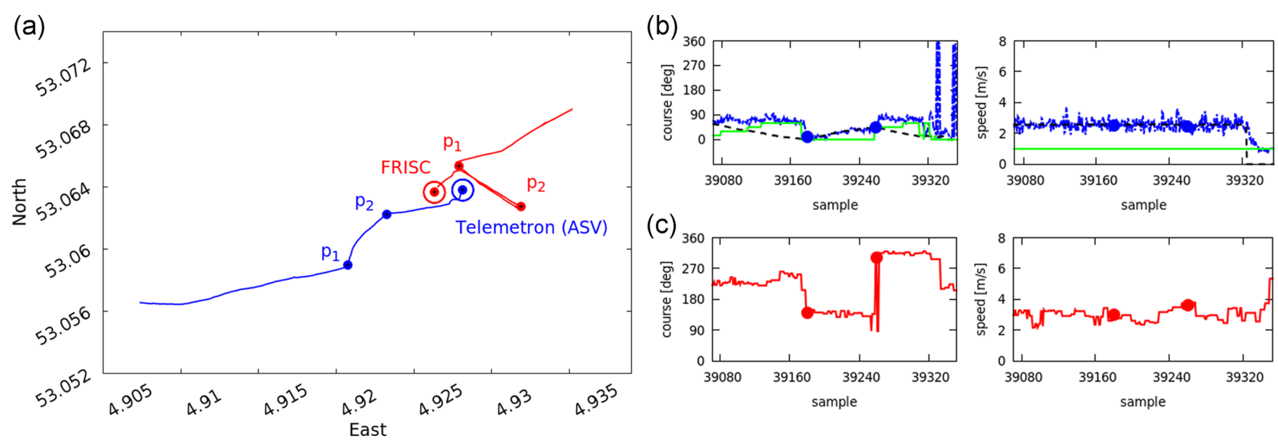


FIGURE 13 Navy versus Fisherman scenario. An uncertain situation with successive head-on and crossing scenarios. (a) Position trajectories. The end of each trajectory is indicated by the symbol ⊙, and the vessels' positions at the same sampling time are indicated by p_1 and p_2. The position of obstacle vessel FRISC is enclosed by a relatively large circular safety region. (b) ASV course χ and speed u. Desired values, χ_d and u_d, from LOS guidance (– – –), course offset χ_m^{k*} and speed factor u_m^{k*} from MPC (——), and measurements (–·–). The points indicate the course and speed at p_1 and p_2 in (a). (c) Obstacle course and speed. ASV, autonomous surface vehicle; FRISC, Fast Raiding, Interception and Special forces Craft; LOS, line-of-sight; MPC, model predictive control [Color figure can be viewed at wileyonlinelibrary.com]

until the scenario was over even though FRISC challenged the ASV's safety region by turning port at the end of the scenario.

6 | DISCUSSIONS

6.1 | ASV performance and robustness to uncertainties

The results presented in Section 5 provide a clear indication that the decision process of the ASV prioritizes predictable behavior in challenging scenarios. The ASV was able to operate satisfactorily in a dynamic environment in varying weather conditions and sea states. Note that the performance achieved reflects the choice of tuning for the MPC strategy as discussed in Section 4.3. It can be seen in, for example, Figures 12c and 13b that there is more activity in the MPC modification for course than that for speed. Since tuning is used to achieve a balance between the different objectives specified through the cost function (1), the tuning can be changed to obtain a different ASV behavior if desirable.

When the speed and course measurements in the different scenarios are compared, it is clear that the noise level in the sensor measurements varied greatly due to different levels of wind forces and waves experienced during the sea trials. For example, Figure 7b,c shows almost perfect sensor measurements for a relatively simple scenario, whereas Figure 9c shows large variations in the measurements for a more complex scenario. However, the varying weather conditions did not affect the performance of the ASV. This indicates that the ASV's collision avoidance decision method is robust to noisy sensor measurements.

A challenging case that motivates further work to improve the ASV's predictability is observed in some test scenarios where the obstacle's intention is unclear. In such cases, the ASV's straight-line prediction of the obstacle's future motion may deviate significantly from the actual motion, leading to reactive maneuvers by the ASV. It is possible to improve the prediction of long-term intention of obstacles based on information transmitted in the obstacle's own AIS signal (e.g., destination) or historic AIS data showing typical behavior of marine vessels in a particular area (Dalsnes, Hexeberg, Flåten, Eriksen, & Brekke, 2018; Hexeberg, Flåten, Eriksen, & Brekke, 2017).

However, in close-range and high-speed encounters, some vessels may choose short-term actions that deviate from their long-term goal/intention. It may therefore be necessary to use more sophisticated obstacle intention prediction models in the ASV's decision process, considering obstacle vessel classification and dynamic capabilities, environmental and ground constraints as well as the interactive behavior that may arise between the vessels involved in a dynamic COLREGs situation. In Kufoalor, Brekke, and Johansen (2018), a strategy that can be applied to MPC collision avoidance methods to incorporate the interactive behavior of marine vessels is studied, and the work in Kufoalor et al. (2019) extends the MPC implementation used during the verification exercise to include robustness strategies that consider possible COLREGs maneuvers by other vessels.

6.2 | Tracking of obstacles based on AIS data

The results presented in Section 5 were achieved based on AIS data received during the tests. The accuracy of the AIS measurements depends on the obstacle vessel's navigation sensors or positioning system, and the accuracy is generally unknown to the ASV. The variations in course and speed measurements seen in Figure 8d, 9d, and 12d for different obstacle vessels show that the accuracy of the measurements received is different for each obstacle. However, for the same weather conditions, the measurements received from larger vessels (e.g., ZIRFAEA in Figure 9d and TH4 ELIZABETH in Figure 8d) are less noisy compared with the measurements of the FRISC.

A crucial aspect of the AIS measurements is the update frequency. The AIS data received is typically updated at least once in 10 s, but the update rate may vary significantly depending on the AIS setup of the transmitting vessel and its maneuvering state as well as interference and AIS overload in areas with high-traffic density. An important observation is that the typical transmission rate of AIS is sufficient for collision avoidance decisions in long-range and low-speed encounters.

Short-range and high-speed obstacle scenarios are more challenging, and may result in reactive ASV behavior, if the AIS data update rate is low. Recall that the MPC method used for collision avoidance decisions (see Section 4.2) prioritizes avoiding collision hazards that are close in time, and due to time and ASV motion constraints, the decision method requires reliable and accurate tracking information about nearby obstacles to be able to make safe and predictable collision avoidance decisions. Large discrepancies between an obstacle's actual motion and the predicted motion due to delays in the AIS updates may therefore lead to undesirable ASV behavior in close-range encounters. Nevertheless, the ASV performed well in most cases due to the robustness properties of the MPC collision avoidance method discussed in Section 4.2.

6.3 | Obstacle tracking fault tolerance

Apart from the possible inaccuracies of AIS measurements discussed in Section 6.2, the transmitted AIS data may be completely wrong. The obstacle vessel may not have AIS or decide to switch off its AIS. The AIS signal may be lost due to transmission faults or interference, and large transmission delays may render the AIS information useless for collision avoidance, especially in close-range encounters.

Although the anomalies listed above are typical of the AIS, other sensors (e.g., radar, lidar, and camera) have their own weaknesses (see, e.g., Elkins, Sellers, & Monach, 2010; Helgesen, 2019; Hermann, Galeazzi, Andersen, & Blanke, 2015; Kufoalor et al., 2019; Larson, Bruch, & Ebken, 2006; Prasad, Rajan, Rachmawati, Rajabally, & Quek, 2017; Schuster et al., 2014; Wilthil, Flåten, & Brekke, 2017). Fusion of several sensors will be needed to enhance the ASV's situational awareness, while fault-tolerant strategies must be implemented to ensure that undesirable events do not lead to dangerous decisions by the ASV.

Further development and research progress in robustness and fault tolerance, using the ASV Telemetron as a case study, are reported in Guzman, Kufoalor, Kozine, and Lundteigen (2019) and Kufoalor et al. (2019).

6.4 | Safety verification and assurance

Although the verification exercise did not focus on fault tolerance, the above observations and lessons learned from the sea trials motivate more research effort into safe, robust, and fault-tolerant autonomous collision avoidance. Moreover, test procedures that aim at providing safety verification and assurance must be able to verify the effects of uncertainty and faults on the behavior of autonomous vessels.

Due to the characteristics of the maritime domain and the associated large variety of dangerous situations that may arise, it is difficult to achieve safety assurance through field verification only. To provide significant statistical evidence of the safety level of autonomous vessels, further research and development is needed in the area of automated verification, where a large variety and a significant number of scenarios can be generated and tested in a simulated environment. In Vartdal and Skjong (2018), DNV GL discusses the requirements and verification procedures needed to provide safety assurance of autonomous vessels, and they highlight the potentials of simulator-based verification. It is however recommended that simulator-based verification is complemented by dedicated field testing for validation purposes.

Note that the simulation approach requires adequate environmental models, vehicle models, and scenario generators that produce relevant test situations from operational specifications, COLREGs, and safety requirements. It is also necessary to develop useful verification metrics that adequately reflect the requirements of COLREGs and assess the general safety level of autonomous vessels. Deriving such metrics in the context of COLREGs-compliance is not trivial, especially for complex scenarios (see Section 2.2) and for requirements that rely heavily on the practice of “good seamanship”. Nevertheless, research efforts, such as Woerner (2016), enable the development of new standards and procedures for automated verification of autonomous vessels.

7 | CONCLUSION

We have presented results from a verification exercise for ASVs in the Dutch North Sea. Both the ASV system architecture and the MPC-based collision avoidance method used were presented. The discussions focused on COLREGs-compliance and the related challenges considering autonomous collision avoidance decision making. The test scenarios presented in this paper cover both typical situations at sea and complex or emergency situations that test the reasoning capabilities of the collision avoidance method.

In contrast to the typical test approach used in research experiments, the field tests in this paper were not carried out by constraining the scenarios to only fixed preplanned behaviors of obstacle vessels. Rather, real traffic scenarios were achieved by allowing regular traffic vessels to enter and exit planned scenarios unannounced. Some scenarios were adapted on the fly by supervisors from the Navy with the aim of exploring challenging situations that may develop due to an unexpected change in behavior. The test approach used by the Navy resulted in interesting scenarios that may be adopted by researchers for field testing and benchmarking of maritime collision avoidance methods.

The MPC-based collision avoidance method tested during the sea trials was able to find safe solutions in challenging situations, and in most cases the ASV demonstrated behaviors that are close to the expectations of the experienced mariners involved in the validation process. The field results are however not sufficient to provide general safety assurance. Different observations from the sea trials that motivate further work on robustness and fault tolerance are discussed in this paper, and we emphasize the need for further work on safety verification of autonomous vessels.

Finally, the achievements of the field verification exercise in the North Sea reveal that the technical maturity of autonomous vessels is approaching a level that will make their deployment desirable in the near future.

ACKNOWLEDGMENTS

The authors from NTNU are grateful to Maritime Robotics for involving them in the field work and tests leading to the results in this paper. We would like to thank Vegard Evjen Hovstein, Thomas Ingebretsen, Joel Pederick, and Andreas Misje from Maritime Robotics for their efforts to make the sea trials with the Telemetron vessel possible, and we are grateful to Stephanie Kemna for her useful comments on this article. We also thank representatives from Deltares, Rijkswaterstaat, the Royal Netherlands Navy, and the Netherlands Coastguard for the initiative, support, and useful discussions during the sea trials. This study was supported by the Research Council of Norway, through the projects 223254 and 244116/O70, and Maritime Robotics AS.

ORCID

D. K. M. Kufoalor http://orcid.org/0000-0003-1836-8818

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How to cite this article: Kufoalor DKM, Johansen TA, Brekke EF, Hepsø A, Trnka K. Autonomous maritime collision avoidance: Field verification of autonomous surface vehicle behavior in challenging scenarios. *J Field Robotics*. 2019;1–17. https://doi.org/10.1002/rob.21919