Ship Collision Avoidance and COLREGS Compliance using Simulation-Based Control Behavior Selection with Predictive Hazard Assessment

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***Abstract*—A relatively small number of alternative collision avoidance control behaviors are formulated by considering nominal and evasive maneuvers.**
The control behaviors are generated by varying two parameters: Offsets to the guidance course angle commanded to the autopilot, and changes to the propulsions command ranging from keep nominal speed to full reverse. Using simulated predictions of the trajectories of the obstacles and ship, the compliances with the COLREGS rules and collision hazards associated with each of the alternative control behaviors are evaluated on a finite prediction horizon into the future, and the optimal control behavior is selected. Robustness to sensing error, predicted obstacle behavior, and environmental conditions can be ensured by evaluating multiple scenarios for each control behavior. The method is conceptually and computationally simple and yet quite versatile and powerful as it can account for the dynamics of the ship, its steering and propulsion system, forces due to wind and ocean current, any number of obstacles. Simulations show that the method is effective and can manage complex scenarios with multiple dynamic obstacles and uncertainty in sensors and predictions.

***Index Terms*—Autonomous Ships; Collision Avoidance; Trajectory optimization; Hazard; Safety; Control Systems.**

I. Introduction

Rules for ship collision avoidance are given by the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS), by the International Maritime Organization (IMO), [1]. Whilst COLREGS were made for ships operated by a crew, their key elements are also applicable for automatic collision avoidance systems, either as decision support systems for the crew or in autonomously operated and unmanned ships [2], [3], [4]. In an autonomous system implementation, COLREGS implicitly impose requirements on the information that must be provided by sensor systems, and what are the correct actions in hazardous situations that could occur.

Autonomous operation of a ship requires that guidance, navigation and control is performed with high reliability, fault-tolerance, and safety, including real-time perception of the ship's surroundings in order to avoid grounding and collision with other ships, vessels, people, marine mammal or other obstacles that may be encountered. Larger ships are expected to carry an AIS (automatic identification system) transmitting radio signals containing position and other information about the ship, that can be received by other ships and authorities. In order to be able to detect the wide range of potential obstacles, onboard sensors such as radar, LIDAR and camera can be used to scan the environment of the ship, [5], [6], [7].

A wide range of ship collision avoidance control algorithms, many of them implementing compliance with the main rules of COLREGS, are reviewed in [8], [9]. Although they generally do not scale very well to manage a large number of highly dynamic obstacles in dense traffic and at the same time can accurately take into consideration the dynamics of the ship, steering and propulsion system, as well as environmental disturbances such as winds and ocean currents. This motivates our investigation on a new appraoch that employs ideas from optimization-based control and can directly exploit the availability of a simulation model for predictions.

Model Predictive Control (MPC) is a very general and powerful control method that can compute an optimal trajectory based on predictions of obstacles motion, robustly account for their uncertainty, employ a nonlinear dynamic vehicle model, and formalize risk, hazard and operational constraints and objectives as a cost function and constraints in an optimization problem. In fact, MPC has been extensively studied for collision avidance in

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automotive vehicles [10], [11], aircraft and air traffic control [12], ground robots [13] and underwater vehicles [14]. Although some elements of optimization and optimal control are used in e.g. [15], [16], the authors are not aware of the use of MPC for ship collision avoidance with COLREGS compliance.

MPC is a powerful method that can compute optimal trajectories using numerical optimization methods. Its main challenges are related to the convergence of the numerical optimization. It is widely recognized that complex collision avoidance scenarios may lead to non-convex optimization formulations exhibiting local minima, and that shortest possible computational latencies is highly desirable for real-time implementation. This makes it challenging to implement an MPC for collision avoidance, and the formulation of models, control trajectory parameterization, objectives, constraints, and numerical algorithms need to be carefully considered along with issues such as dependability [17].

In order to reap the main benefits of MPC, and avoid the issues related to local minima, computational complexity and dependability, we take a rather simple approach that turns out to be very effective in terms of high performance and low complexity of implementation. In the literature on robust MPC the concept of optimization over a finite number of control behaviors is well known and widely used, e.g. [18], [19], [20]. In its simplest form, it amounts to selecting among a finite number of control behaviors based on a comparison of their cost and feasibility, e.g. [21], [22], [23], although most approaches also incorporates optimization over some control parameters. In this paper, we will consider a relatively small finite number of control behaviors, and merely require evaluation of performance by simulation and hence completely avoid numerical optimization and the associated computation of gradients. This certainly restricts the degrees of freedom available for control, and the selection of the set of alternative control behaviors must be carefully considered in order to ensure the required control performance and effectiveness of the collision avoidance system and COLREGS compliance.

We propose to implement collision avoidance functionality through a finite horizon and finite scenario hazard minimization problem over a finite number of control behaviors. The optimization problem is solved in a receding horizon implementation with a re-optimization based on updated information at regular intervals, e.g. every 5 seconds. The hazard associated with the ship trajectory resulting from a given control behavior is evaluated using a ship simulator to make predictions that takes into account the dynamics of the ship, steering and propulsion system, the current position and velocity, the control behavior, as well as wind and ocean current. Robustness can be guaranteed by considering additional scenarios resulting from perturbation of the input data. A cost function considers the constraints and objectives of collision avoidance and compliance with the rules of COLREGS, using velocity and line-of-sight vectors to express the COLREGS rules. The constraints are implemented as penalties in order to ensure that the best possible control behavior can be chosen also when collision with at least one obstacle seems unavoidable. The new method takes advantage of some formulations and ideas in [24], [25], [26], [15] that are embedded into the optimization formulation. We emphasize that the proposed optimization is deterministic and guarantees that the global minimum is found after a pre-defined number of cost function evaluation, in contrast to e.g. evolutionary algorithms where the convergence cannot in generall be guaranteed in a finite number of cost function evaluated.

The proposed architecture implies that the collision avoidance functionality is separated from the mission planning functionality, and the commands from both these systems are executed by the ship's autopilot. This leads to a highly modular architecture that admit the collision avoidance system to be added on top of existing functionality, and such that reliability and safety can be ensured through additional independent and redundancy systems and functions.

II. System overview

In order to support the collision avoidance we assume the following information and capacities are available

- List of obstacle's positions and velocities, from radar, lidar, AIS, camera or infrared thermal imager, or similar sensors and systems.
- Mapped hazards from an electronic map.
- A desired nominal path to the target destination.
- Mathematical model of ship for prediction of future trajectory in order to evaluate the effect of steering and propulsion commands, as well as winds and ocean currents.
- Real-time measurement of the ship's position, velocity, heading and yaw rate.
- Estimates of wind and ocean current forces on the ship.

Figure 1 illustrates the sub-systems and the information flow between them. The nominal input to the ship's Autopilot from the Mission Planner is assumed to be the propulsion or speed-over-ground command, and the desired path described through a sequence of way-points. The Collision Avoidance System (CAS) searches for

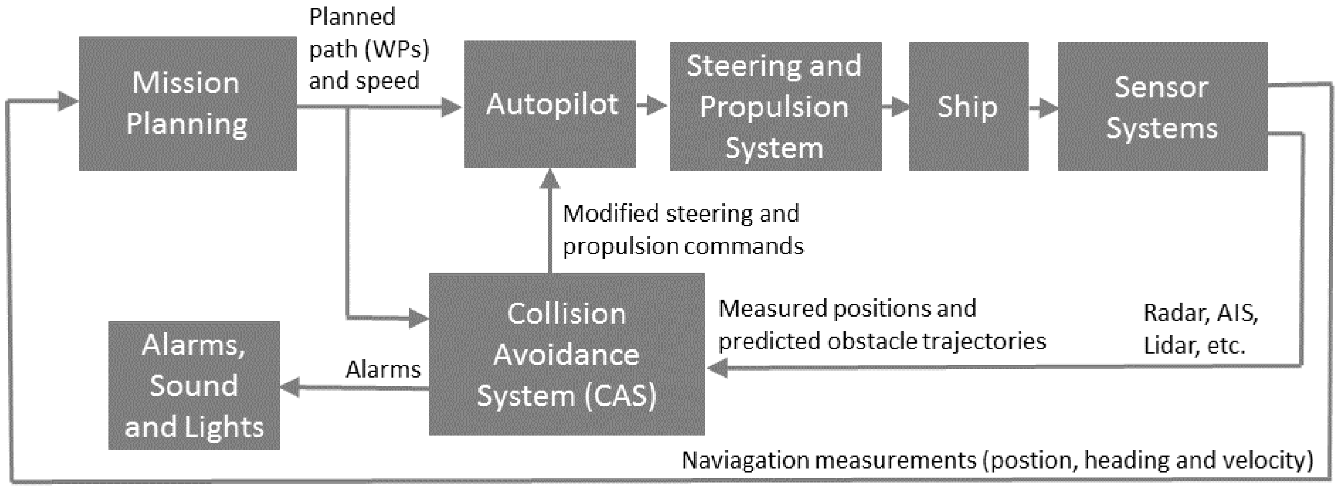

Fig. 1. Block diagram illustrating the information flow between the main modules in the system.

collision-free trajectories close to the ship's nominal trajectory, given the measured positions and predicted trajectories of obstacles. The CAS outputs a course angle offset and a modified propulsion command that are given to the autopilot. We notice that the CAS needs to consider trajectories (with explicit representation of time) while in the autopilot there is a decoupling of position and time into path guidance (steering) and propulsion control. The speed is normally kept close to a nominal cruise speed, but may be reduced, set to zero, or reversed, upon command from the Collision Avoidance System (CAS). The CAS can also provide alarms such as sound and light signals. In-depth descriptions of the CAS functionality are given in section III.

The ship's onboard navigation system provides measurements (usually from a global navigation satellite system (GNSS)) of position and velocity, typically using sensor fusion.

A brief overview of the main rules of COLREGS are given in Appendix A.

III. Collision avoidance system (CAS)

The collision avoidance problem is linked with considerable uncertainty, as the obstacles' future motions must be predicted. The simplest short-term predictions of the obstacles' trajectories are perhaps straight line trajectories

$$\overline{\eta}_i^{lat}(t) = \hat{\eta}_i^{lat} + k_{lat}\hat{v}_i^N(t-\tau_i) \tag{1}$$

$$\overline{\eta}_i^{long}(t) = \hat{\eta}_i^{long} + k_{long}\hat{v}_i^E(t-\tau_i) \tag{2}$$

where k_{lat} and k_{long} are constants that convert from meters to degree in the given area, t a future point in time, and τ_i is the time of last observation. Whilst COLREGS define a set of traffic rules that leads to expected behaviors, one must also be prepared for the fact that some vessels will not be able, or choose not, to comply with these rules.

Based on this, we make some choices and assumptions

- The CAS decides its control behavior by evaluating a finite number of alternative control behaviors in some scenarios using a ship simulator that operates much faster than real time. Each scenario is defined by the current state of the ship, the predicted trajectories of the observed obstacles, a control behavior that is either assumed to be fixed on the prediction horizon or by a sequences of control behaviors that are used in different parts of the prediction horizon. The nominal scenario (guidance along the nominal path with no course offset and at nominal speed) is accepted if the hazard is sufficiently low. If not, the least hazardous control behavior is selected among the alternatives that represent a finite number of evasive control behaviors. The predictive simulation should include effects of winds and currents that may have a significant effect on the ship, in particular if the decided control action is to stop.
- The hazard minimization criterion is based on an evaluation of collision hazard, grounding hazard and COLREG compliance. The strategy recognizes that there may be conflicting objectives and constraints, such that a sound compromise must be made to determine minimum hazard.

Next, the alternative control behaviors and hazard criterion are described in more detail.

A. Control behaviors and scenarios

The set of alternative control behaviors should be as extensive as computation time allows, since this will increase the performance of the system. The following set of alternative control behaviors is to be considered as a minimum implementation

- Course offset at -90, -75, -60, -45, -30, -15, 0, 15, 30, 45, 60, 75, 90 degrees
- Keep speed (nominal propulsion), slow forward, stop and full reverse propulsion commands.

and all the combinations of the above leading to $13 \cdot 4 = 52$ control behaviors. Assuming the control behavior is kept fixed on the entire prediction horizon, this corresponds to 51 evasive maneuvers in addition to the nominal control behavior with zero course offset, and nominal forward propulsion. Clearly, considering the possibility to change control behavior on the horizon may lead to a ship trajectory with less hazard. However, with one change in control behavior on the horizon this leads to a much larger number of $52^2 = 2704$ scenarios. From a safety point of view it is clearly desirable to evaluate as many alternative scenarios as possible, while from a computational point of view the number of scenarios needs to be kept smaller than the computational capacity. There is clearly also a trade-off between the number of scenarios and the computational complexity of the simulations in terms of high-fidelity time-discretization, length of prediction horizon, detail of ship model, control update interval and latency. Robustness to uncertainty in the prediction of the obstacle's trajectories may also be represented by additional scenarios being perturbations of the obstacles' predicted trajectories, see Section IV-B.

In order to predict the ship's motion in response to the different control behaviors as well as wind and ocean current disturbances, we propose to employ the standard 3-degrees of freedom horizontal plane ship dynamics model, neglecting the roll, pitch and heave motions [27]

$$\begin{aligned} \dot{\eta} &= R(\psi)v + v_c \\ M\dot{v} + C(v)v + D(v)v &= \tau + R(\psi)^T \tau_w \end{aligned} \tag{3}$$

where $\eta = (x, y, \psi)$ represents position and heading in the earth-fixed frame, $v = [v_x, v_y, r]$ includes surge and sway velocities in the body-fixed frame and yaw rate, M is the vessel inertia matrix, $C(\cdot)$ and $D(\cdot)$ model, respectively, Coriolis and damping terms, $R(\psi)$ is the rotation matrix from body-fixed to earth-fixed frame, the input τ represents the commanded thrust and moments, and v_c, τ_w are the contributions of ocean current and wind force, both expressed in the earth-fixed frame.

The simulation should account for the dynamics of the propulsion and steering system, an autopilot that accept a course command to implement the steering control. We assume the autopilot is executing a LOS guidance control with a given look-ahead distance, [28]. This leads to a course command χ_{LOS} that guides the ship towards the straight path between the previous and the current selected way-points. The CAS can provide a course angle offset χ_{ca} such that the actual course command is $\chi_c = \chi_{LOS} + \chi_{ca}$. A PI controller for the course steering is then implemented to compute the commanded rudder angle

$$\delta = K_p(\chi_c - \chi) + K_i \int_0^t (\chi_c - \chi) dt \tag{4}$$

where K_p and K_i are controller gains. The autopilot operates with a constant propulsion command $P \in [-1, 1]$ where 1 is (nominal) forward propulsion, 0 is stop, and -1 is full reverse. A highly useful property of these control behaviors is that they represent meaningful actions when the control behavior is kept constant on the whole prediction horizon. Another useful property is that since the course offset comes in addition to the LOS guidance, then simply setting the course offset to zero will recover the LOS guidance control and the ship will go back to the nominal path without any further planning or guidance.

B. Hazard evaluation criteria

An important factor in the evaluation of collision hazards is the prediction horizon used to evaluate the result of the simulation scenarios described in Section III-A. COLREGS rules 8 and 16 demand that early action is taken, so the prediction horizon should be significantly larger than the time needed to make a substantial change of course and speed.

The main information used to evaluate collision hazard at a given future point in time on a predicted ship trajectory generated by a candidate control behavior is illustrated in Figure 2, and detailed as follows:

- The blue curve illustrates the own ship's predicted trajectory, which is a function of the current position, velocity and heading, as well as the control behaviors, nominal path given by the way-points, and environmental forces, cf. Section III-A.
- The red curve illustrates the predicted trajectory of the obstacle with index i, which is a straight line based on the most recent estimate of position and velocity, cf. (1)-(2).
- The blue and red dots denote the predicted position at some future time instant t, while the blue and red vectors illustrate the predicted velocity of own ship and obstacle with index i in scenario k, denoted by the vectors $\vec{v}_0^k$ and $\vec{v}_i$ respectively.

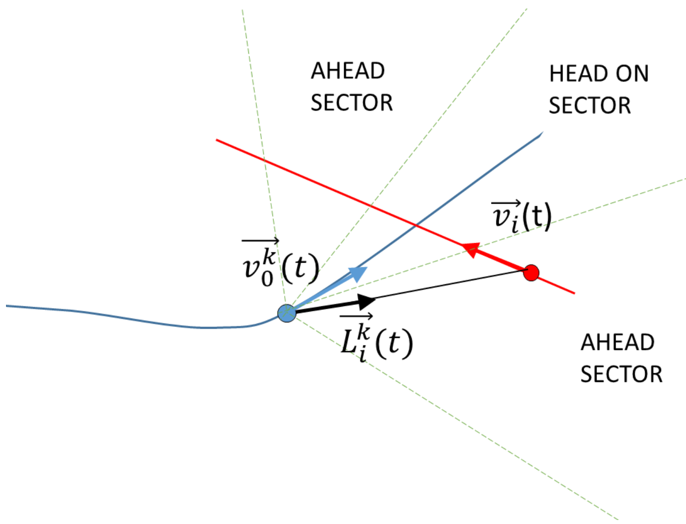

Fig. 2. The main information used for hazard evaluation at a given future time t in scenario k, where the blue dot denotes the predicted position of the own vehicle, and the red dot denotes the predicted position of an obstacle with index i.

- The black vector is a unit vector in the LOS direction from own ship to the obstacle with index i in scenario k, denoted $\vec{L}_i^k$.
- The ship is said to be OVERTAKEN by the obstacle with index i at time t in scenario k if

$$\vec{v}_0^k(t) \cdot \vec{v}_i(t) > \cos(68.5°)|\vec{v}_0^k(t)||\vec{v}_i(t)| \qquad (5)$$

  and it has higher speed, and is within a distance d_{ot} of own ship.
- The obstacle with index i is said to be STARBOARD of own ship at time t in scenario k if the bearing angle of $\vec{L}_i^k(t)$ is larger than the heading (yaw) angle of own ship.
- The obstacle with index i is said to be HEAD-ON at time t in scenario k if the obstacle speed $|\vec{v}_i(t)|$ is not close to zero and

$$\vec{v}_0^k(t) \cdot \vec{v}_i(t) < -\cos(22.5°)|\vec{v}_0^k(t)||\vec{v}_i(t)| \qquad (6)$$
$$\vec{v}_0^k(t) \cdot \vec{L}_i^k(t) > \cos(\phi_{ahead})|\vec{v}_0^k(t)| \qquad (7)$$

  where ϕ_{ahead} is an angle to be selected.
- The obstacle with index i is said to be CROSSED at time t in scenario k if

$$\vec{v}_0^k(t) \cdot \vec{v}_i(t) < \cos(68.5°)|\vec{v}_0^k(t)||\vec{v}_i(t)| \qquad (8)$$

  where 68.5° could be replaced by a more suitable angle depending on the velocity and type of obstacle.
- The obstacle with index i is said to be CLOSE to own ship at time t in scenario k if $d_{0,i}^k(t) \leq d_i^{cl}$. Here $d_{0,i}^k(t)$ is the predicted distance between own ship and obstacle with index i at time t in scenario k, taking into account the shape, size and heading of the obstacle and own ship. Moreover, d_i^{cl} is the smallest distance where the COLREGS responsibilities for stay away are considered to apply. This distance may depend on the obstacle's and own ship's speed, as well as other factors.

Based on these definitions, we define the collision risk factor

$$\mathcal{R}_i^k(t) = \begin{cases} \frac{1}{|t-t_0|^p}\left(\frac{d_i^{safe}}{d_{0,i}^k(t)}\right)^q, & \text{if } d_{0,i}^k(t) \leq d_i^{safe} \\ 0, & \text{otherwise} \end{cases}$$

where t_0 is the current time, $t > t_0$ is the time of prediction. The distance d_i^{safe} and the exponent $q \geq 1$ must be chosen large enough to comply with COLREGS rule 16, i.e. to take substantial action to keep well clear. This implies that d_i^{safe} may depend on the uncertainty of the prediction of obstacle i's trajectory. Moreover, d_i^{safe} is should take into account COLREGS rule 18 by ensuring sufficient safety distance to ships that are fishing, sailing, or appear to not be under command or with restricted ability to maneuver. The exponent $p \geq 1/2$ describes how risk is weighted as a function of the time until the event occurs. The inverse proportionality with the time until occurrence of the event means that avoiding collision hazards that are close in time is being prioritized over those that are more distant. This is important as the sensory information and short-term predictions of the obstacle trajectories are usually more accurate than long-term predictions, and there is more time to take action. Typical choices are $q = 4$ and $p = 1$.

We choose the cost associated with collision with obstacle with index i at time t in scenario k as

$$\mathcal{C}_i^k(t) = K_i^{coll}|\vec{v}_0^k(t) - \vec{v}_i^k(t)|^2$$

This cost scales with the kinetic energy as given by the relative velocity of the obstacle and own ship, which may be important to consider if ending up in a situation with multiple obstacles and collision may be unavoidable. The factor $K_i^{coll}(t)$ may depend on several properties such as the type of the obstacle and its size (domain), and own ship's right to stay on or responsibility to keep out of the way.

Let the binary indicator $\mu_i^k \in \{0,1\}$ denote violation of COLREGS rule 14 or 15 between own ship and the obstacle with index i at time t in scenario k, respectively, where the logic expressions are given by

$$\begin{aligned} \mu_i^k(t) &= \text{RULE14} \mid \text{RULE15} \\ \text{RULE14} &= \text{CLOSE} \ \& \ \text{STARBOARD} \ \& \ \text{HEAD-ON} \\ \text{RULE15} &= \text{CLOSE} \ \& \ \text{STARBOARD} \ \& \ \text{CROSSED} \\ & \quad \& \ \text{NOT OVERTAKEN} \end{aligned}$$

This incorporates rule 13 which states that it is the overtaking vessel that shall keep out of the way.

The hazard associated with scenario k, as predicted based on the available information at time t_0, is then

$$\mathcal{H}^k(t_0) = \max_i \max_{t \in D(t_0)} \Big(\mathcal{C}_i^k(t)\mathcal{R}_i^k(t) + \kappa_i \mu_i^k(t) \Big) + f(P^k, \chi_{ca}^k) + g(P^k, \chi_{ca}^k)$$

where t_0 is the current time, and the discrete sample times are given in $D(t_0) = \{t_0, t_0 + T_s, ..., t_0 + T\}$, T_s is the discretization interval, T is the prediction horizon, and

$$f(P, \delta) = k_P(1 - P) + k_\chi \chi_{ca}^2 + \Delta_P(P - P_{last}) + \Delta_\chi(\chi_{ca} - \chi_{ca,last})$$

where Δ_P and Δ_χ are penalty functions that are positive at the origin. The functions k_χ and Δ_χ are generally asymmetric and gives a higher penalty on course offset commends to port than starboard, in compliance with COLREGS rules 14, 15 and 17. The term $g(\cdot)$ represents a grounding penalty that should be defined based on electronic map data and possibly ship sensor data. The term f is included in order to favor a predictable straight path with constant cruising speed, if possible, as required by COLREGS rule 17. The two last terms in f are included to ensure that the control behavior is not changed unless it gives a significant reduction in the hazard, in order to further enhance the predictability of the ship's control actions.

The control behavior with minimal $\mathcal{H}^k(t_0)$ is selected among the scenarios $k \in \{1, 2, ..., N\}$ at time t_0:

$$k^*(t_0) = \arg\min_k \mathcal{H}^k(t_0) \tag{9}$$

This minimization is executed by evaluating all the scenarios and comparing their hazard. The optimal control behavior is communicated to the autopilot that executes the action. The minimization is repeated at regular intervals, e.g. every 5 seconds, in order to account for new sensor information that has been acquired and processed since the previous optimization was executed.

There are several tuning parameters involved. Some of them are critical to achieve the intended behavior of the algorithm, while some of them primarily influences which actions to take when there are conflicting objectives. Whilst the selection of these parameters is critically important, one need to consider other factors in their tuning, such as technological, economical, ethical and legal aspects beyond COLREGs. This is considered to be outside the scope of this paper.

IV. Robustness

There are several ways for uncertainties to affect the algorithm and, consequently, to increase the hazard of the selected maneuvers. It is therefore crucial to enhance the algorithm by letting it be capable of evaluating additional scenarios corresponding to uncertain cases. The main aspects to be taken care of are: uncertainty on the obstacle position, uncertainty in the obstacle motion prediction, and presence of environmental disturbances. The robust schemes to be adopted for dealing with such situations will be discussed in this section.

A. Uncertainty on obstacle position

The estimated position of the obstacles is determined by fusing together the information gathered from the sensors onboard. The estimation accuracy may vary from good to poor depending on several factors, such as obstacle size and shape as well as meteorological conditions; as a matter of fact, the radar and optical sensors performances are markedly weakened in the presence of rain and fog.

Suppose that, at a given time instant, the measured position of the i^{th} obstacle $(\hat{\eta}^{lat}, \hat{\eta}^{long})$ is not uniquely determined, with

$$(\hat{\eta}_i^{lat}, \hat{\eta}_i^{long}) \in \mathcal{D}_i$$

for some bounded region $\mathcal{D}_i$. A simple and straightforward method to process such uncertainty is to consider the spherical hull of the uncertainty region $\mathcal{D}_i$:

$$\rho_{\eta,i} := \arg\min_{r>0} \mathcal{B}_r \supseteq \mathcal{D}_i$$

where $\mathcal{B}_r$ denotes an arbitrary circle of radius $r > 0$. Let $(\eta_{\flat,i}^{lat}, \eta_{\flat,i}^{long})$ be the center of the spherical hull, such that

$$\mathcal{B}_{\rho_\eta,i} = \{(\eta_1, \eta_2) : \sqrt{(\eta_1 - \eta_{\flat,i}^{lat})^2 + (\eta_2 - \eta_{\flat,i}^{long})^2} \leq \rho_{\eta,i}\}.$$

Then the hazard estimation algorithm can be executed robustly with respect to the uncertainty by replacing $(\hat{\eta}_i^{lat}, \hat{\eta}_i^{long})$ with $(\eta_{\flat,i}^{lat}, \eta_{\flat,i}^{long})$ and considering the augmented distances

$$d_i^{safe} = d_i^{safe} + \rho_{\eta,i}$$
$$d_i^{cl} = d_i^{cl} + \rho_{\eta,i}$$

Moreover, the predicted distance from the obstacle $d_{0,i}^k(t)$ has now to be computed with respect to the center of the spherical hull, i.e. as the predicted distance of the own ship from the geometric point $(\eta_{\flat,i}^{lat}, \eta_{\flat,i}^{long})$. It is worth noticing that, due to the definition of collision risk in the proposed cost function, the set of obstacle admissible positions $\mathcal{B}_{\rho_\eta,i}$ is not uniformly weighted: positions near the center $(\eta_{\flat,i}^{lat}, \eta_{\flat,i}^{long})$ are promptly associated to a greater hazard compared to those near the boundary $\partial\mathcal{B}_{\rho_\eta,i}$. On the other hand, measurements inaccuracy is likely to decrease when the obstacles become closer, this resulting in a limit condition

$$\rho_{\eta,i} \to 0 \text{ as } d_{0,i} \to 0.$$

B. Uncertainty on obstacle motion prediction

The prediction of the obstacle motion is a critical point in the algorithm reliability, but it is naturally prone to uncertainty. Assuming that the obstacles move along a straight path at a constant speed is sufficient to avoid hazardous maneuvers in many cases but, in certain scenarios, this might turn out to be too naive and potentially dangerous. A straightforward way to account for uncertainties, and still affordable in terms of computational burden, is to include some additional scenarios, corresponding to the inclusions $|\vec{v}_i(t)| \in \mathcal{V}_i,\ \beta_i \in \mathcal{Z}_i$ where $|\vec{v}_i(t)|, \beta_i$ are respectively the speed and the bearing of the ith obstacle and $\mathcal{V}_i,\ \mathcal{Z}_i$ are discrete sets that include the "straight path" scenario. For instance, given the predicted values $v_i^*\ m/s$ and β_i^* degrees, a possible and simple choice for the sets $\mathcal{V}_i,\ \mathcal{Z}_i$ is

$$\mathcal{V}_i = \{v_i^* - 1\ m/s,\ v_i^*,\ v_i^* + 1\ m/s\},$$
$$\mathcal{Z}_i = \{\beta_i^* - 3^\circ,\ \beta_i^*,\ \beta_i^* + 3^\circ\}.$$

It must be pointed out that an additional source of uncertainty comes from evasive maneuvers performed by other ships, especially in a multi obstacles scenario. As a matter of fact, configurations are admissible such that the application of COLREGs by one of the obstacles might lead to a scenario with a greater hazard compared to the one occurring when all the incoming vessels follow standard straight paths. For this reason, it might be worth to enhance the hazard evaluation scheme by considering some additional scenarios, corresponding to situations like

"i^{th} obstacle alters its course to STARBOARD".

Clearly, one major challenge is the uncertainty on the time-step when the action is taken by the vessel.
The algorithm improvement can be formally done evaluating, in addition to the standard cases, also the following set of obstacle maneuvers, corresponding to a change of course taken at any time-step in the prediction horizon:

$$\left\{ \begin{array}{l} \text{SCENARIO } \mathcal{N}_{i,k},\ k = 1, ..., N : \\ \beta_i(t_0 + k) = \beta_i(t_0 + k - 1) + \delta\beta \\ \beta_i(t_0 + \ell) = \beta_i(t_0 + k)\ \forall \ell \geq k \end{array} \right\}$$

where $\delta\beta$ is a fixed course offset to STARBOARD. Such parameter may depend on vessel size and type, as well as from the distance between other vessels and/or grounding hazards. The enhanced algorithm will be referred to as *extended* COLREGs-*compliant* framework.

C. Disturbances

Let us finally analyze the case of environmental disturbances. Even though the autopilot is generally capable of compensating for the effect of wind, ocean current and waves while the vehicle is in motion, the presence of disturbances cannot be neutralized when the ship is commanded to stop or to make a sharp turn: drifts or limited turning capabilities are likely to occur in practice. Thus, when evaluating the best control action, it is worth to take into account the additional input provided by the overall environmental disturbance in order to prevent the selection of scenarios with a potential hazard in the case of perturbed motion, e.g. the natural drift when the vehicle is stopped.
Suppose that a sufficiently accurate estimate of the environmental disturbances $\tilde{v}_c$ and $\tilde{\tau}_w$ is made available (offline) at any admissible position for the ship. Including such terms in the ship motion prediction, some noticeable changes in the evaluation of the control behaviors arise:

- The action $P = 0$ corresponds to the ship predicted response to the estimated disturbances $\tilde{v}_c$ and $\tilde{\tau}_w$ without any control input.
- The action "Course offset" includes the effect of the external inputs $\tilde{v}_c$ and $\tilde{\tau}_w$ on the turning rate.

V. SIMULATIONS

The simulation results are illustrated in figures representing snapshots of situations. The following symbols and color codes are applied:

- In the North-East position plots, the black straight line is the path between the two way-points. The black curve is the path of the own ship up to a final time. The small circle denotes d_i^{safe} while the larger circle denotes the d_i^{cl} distance. The green curves denote the paths of the obstacles up to a final time marked by a small green circle. If there are multiple obstacles, their paths are identified by a number. The thick red curve denotes the anti-grounding constraint.
- The Steering and Propulsion plot shows the propulsion command (dark blue) and rudder angle (black) as a function of time.
- The Hazard plot shows the selected (optimal) hazard $\mathcal{H}^{k^*(t_0)}(t_0)$, with the selected control behavior, as a function of time.

The same tuning parameters of the hazard criterion is used in all cases.

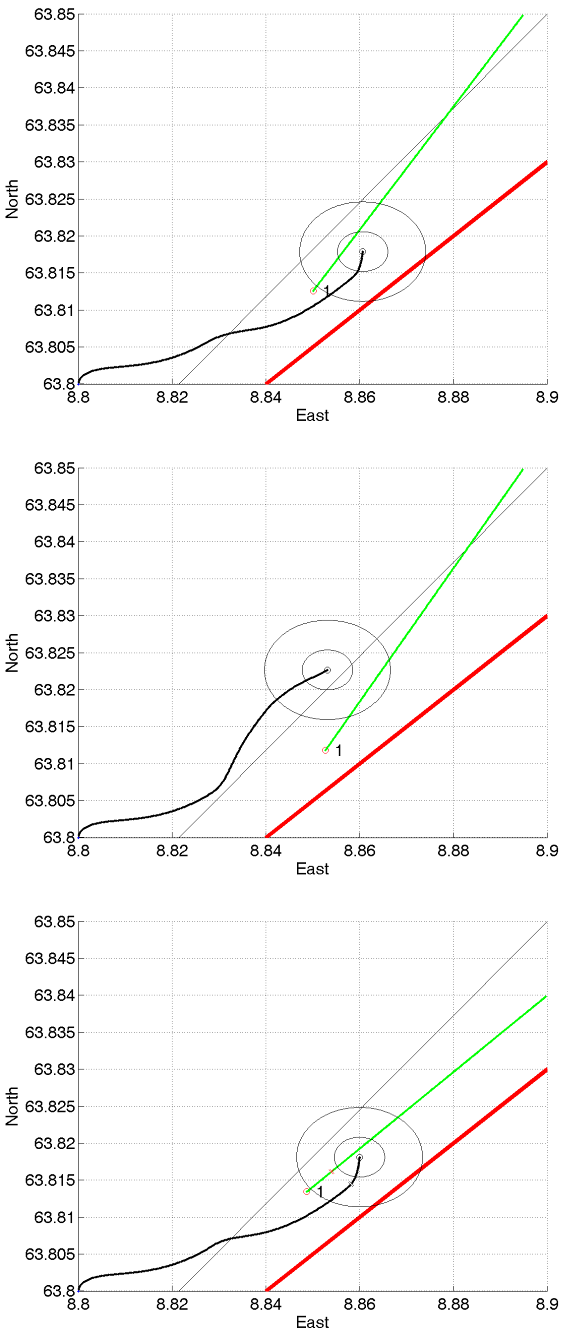

Fig. 3. Single obstacle head-on simulation.

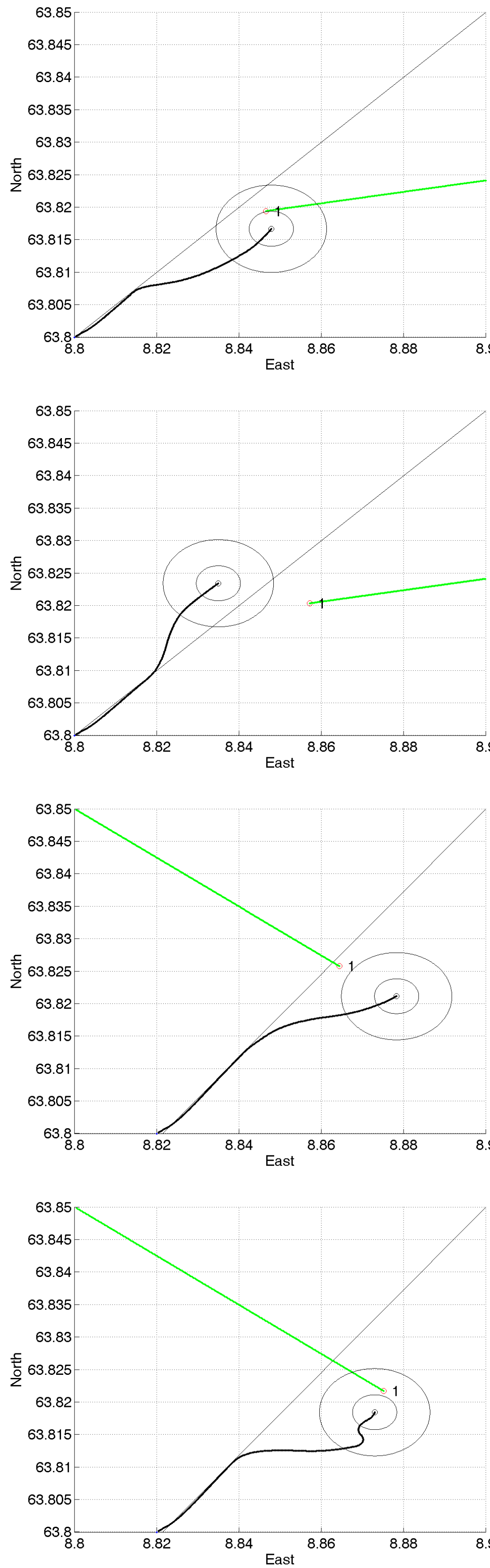

Fig. 4. Single obstacle crossing simulation.

A. Single obstacle collision avoidance

Simulations with single obstacle head-on scenarios are given in Figure 3. It can be seen that the ship behavior complies with COLREGS rule 14 and changes course to starboard and passes with the obstacle on her port side when this is safe with respect to collision and grounding. If the distance between the ship and obstacle is so large that COLREGS are considered not to apply, the ship changes course to port and have the obstacle on her

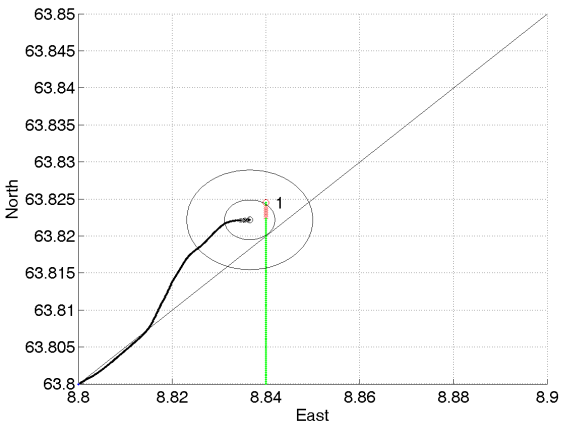

Fig. 5. Single obstacle overtaking simulation.

starboard side since this path is closer to the nominal path. The tuning could easily be changed to slow down or stop instead of change course to port, if desired.

Simulation with a single obstacle crossing scenarios are given in Figure 4. The two first cases show an obstacle arriving from the starboard side such that the own ship shall keep away. The ship can either pass ahead or abaft of the obstacle, depending on which trajectory gives smallest deviation from the nominal path. In the two last cases the obstacle arrives from the port side such that the own ship has right to stay on. In these scenarios the obstacle does not respect its responsibility to keep away and the ship makes a maneuver to avoid collision with some margin. The ship can either pass ahead or abaft of the obstacle, depending on which trajectory gives smallest deviation from the nominal path.

Figure 5 shows the result of a simulation where the obstacle arrives from abaft and overtakes the own ship. The obstacle makes no attempt to keep away, so the own ship makes a maneuver to avoid collision, and crosses abaft of the obstacle.

In all these cases the own ship continued on nominal propulsion command, as COLREGS compliance and collision avoidance was achieved by change of course only.

B. Collision avoidance with multiple obstacles

Simulations with multiple obstacles have also been considered. In Figure 6 and Figure 7 an head-on scenario with several vessels is presented. In the first case the selected control behavior corresponds to a course offset toward starboard side, while in the second case a large turn on the port side has been evaluated as the best possible action. Crossing from starboard side scenarios have been reported in Figure 8 and Figure 9: according

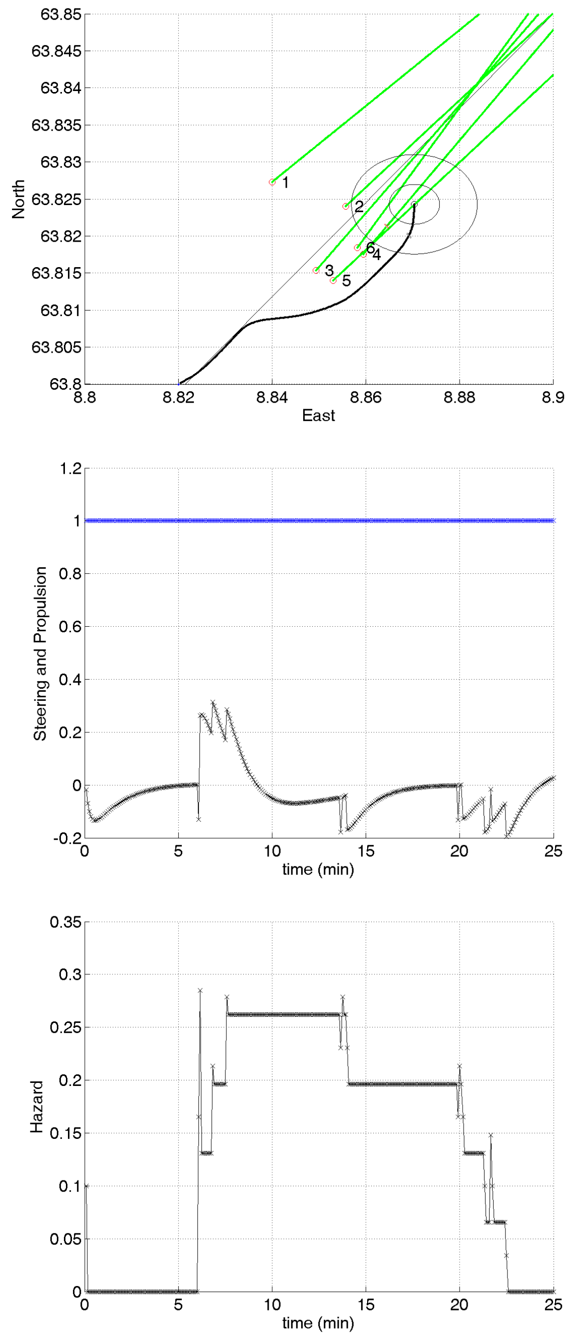

Fig. 6. Multiple obstacles head-on simulation.

to COLREGS, the own vessel is requested to stay away. Figures 10-11 illustrate instead the case when the own vessel has the right to stay on.

C. Robustness enhancement

Figure 11 represents a challenging case. While the resulting trajectory is safe, it cannot be said to be very predictable. The control behavior selection suffers from the fact that there is no obvious optimal solution and

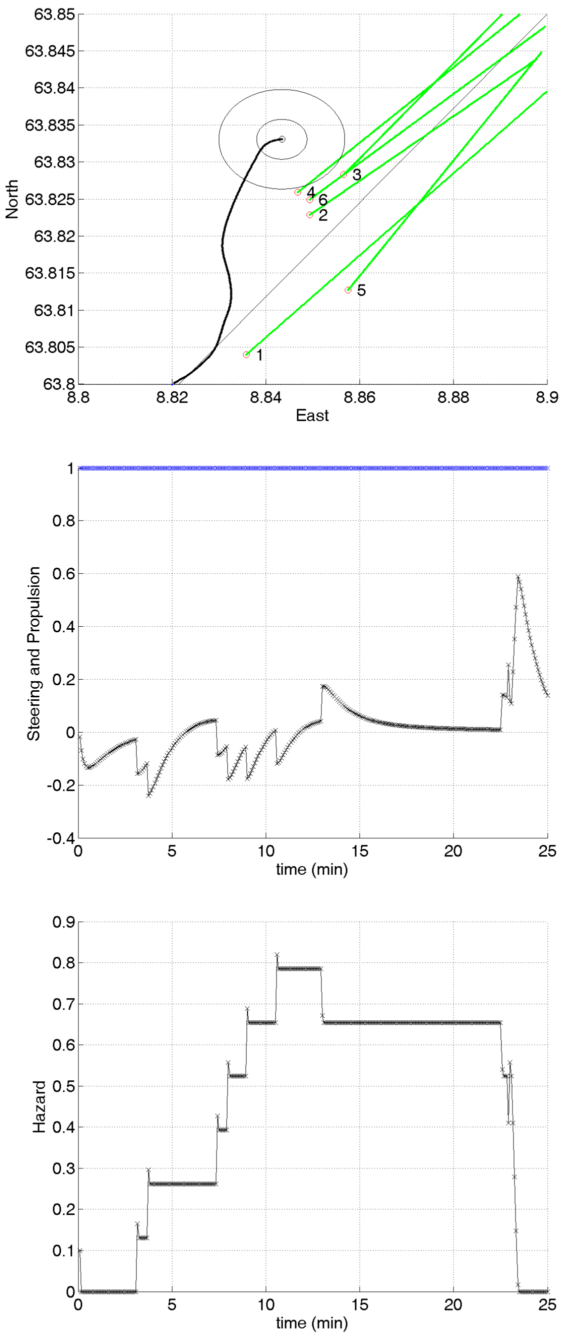

Fig. 7. Multiple obstacles head-on simulation

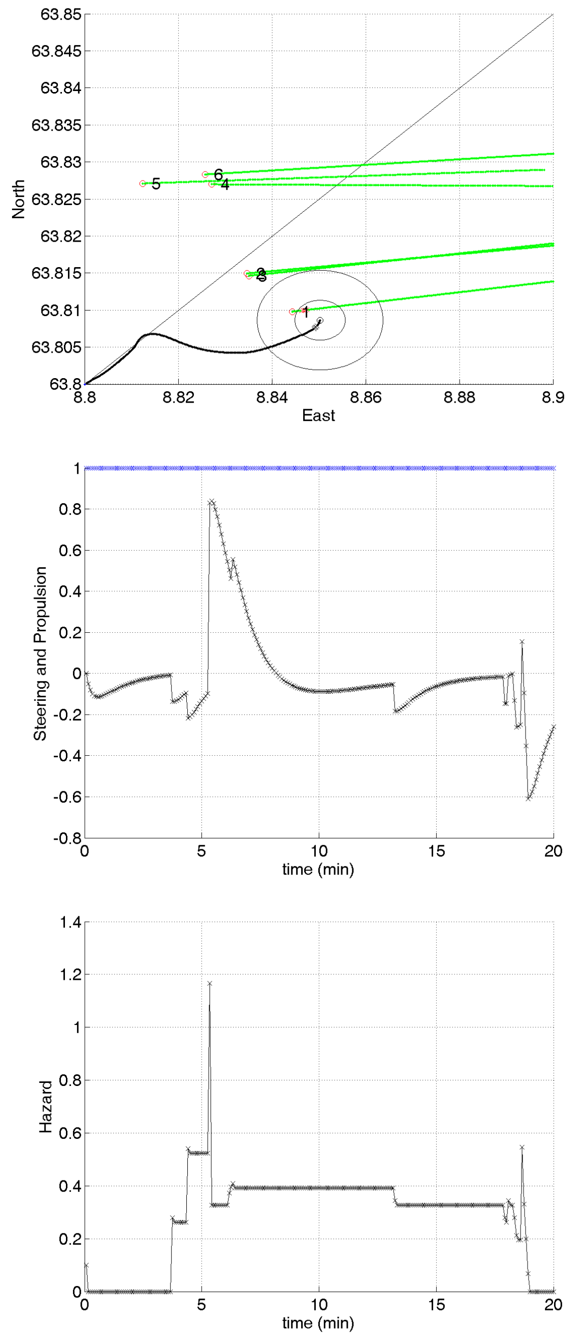

Fig. 8. Multiple obstacles crossing simulation, where own vessel has responsibility to stay away.

early sub-optimal decisions are taken on the basis on the incomplete information available due to the finite prediction horizon (some obstacles are seen before the others). A more robust control behavior selection is enforced by adding four new scenarios that are generated as perturbations to the predicted obstacle trajectories. The four new scenarios for each obstacle consider $\pm 1\ m/s$ error in speed, and $\pm 3^{\circ}$ error in bearing angle. It can be seen in Figure 12 that the resulting control behaviour is more cautious and conservative, and also leads to a smoother and more predictable trajectory of the ship.

The evaluation of the extended COLREGs-compliant framework described at the end of Section IV-B is depicted in Figure 13. The considered scenario is characterized by the own vessel that is overtaken by a faster vehicle while simultaneously is facing a starboard crossing. In the nominal case, the selected control behavior

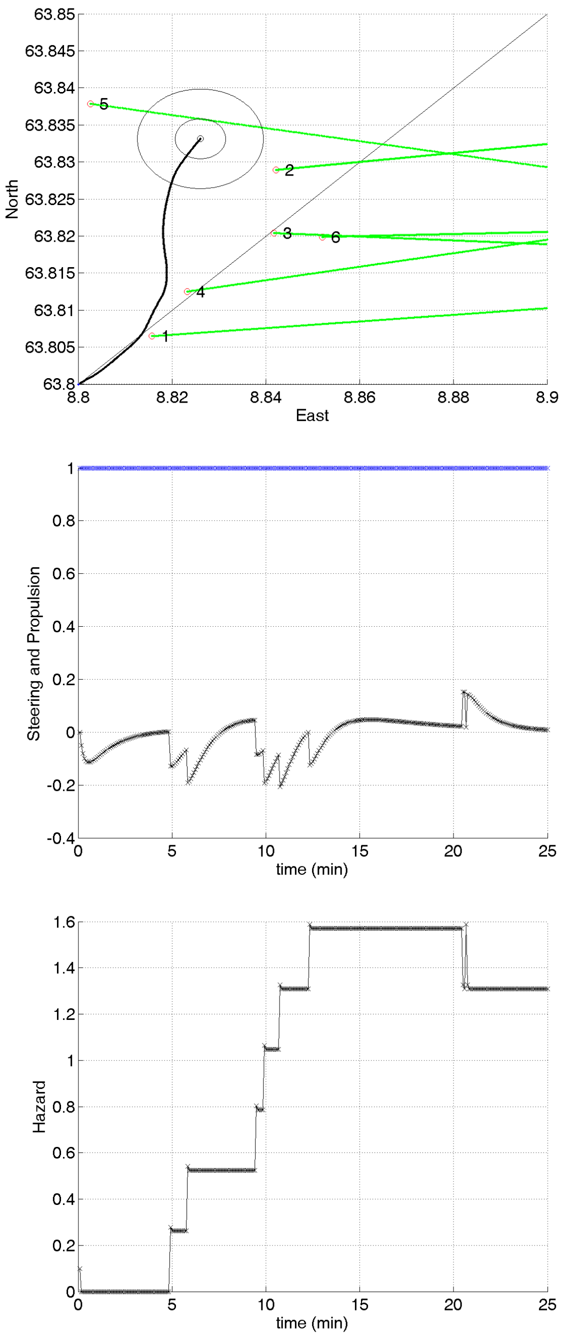

Fig. 9. Multiple obstacles crossing simulation, where own vessel has responsibility to stay away.

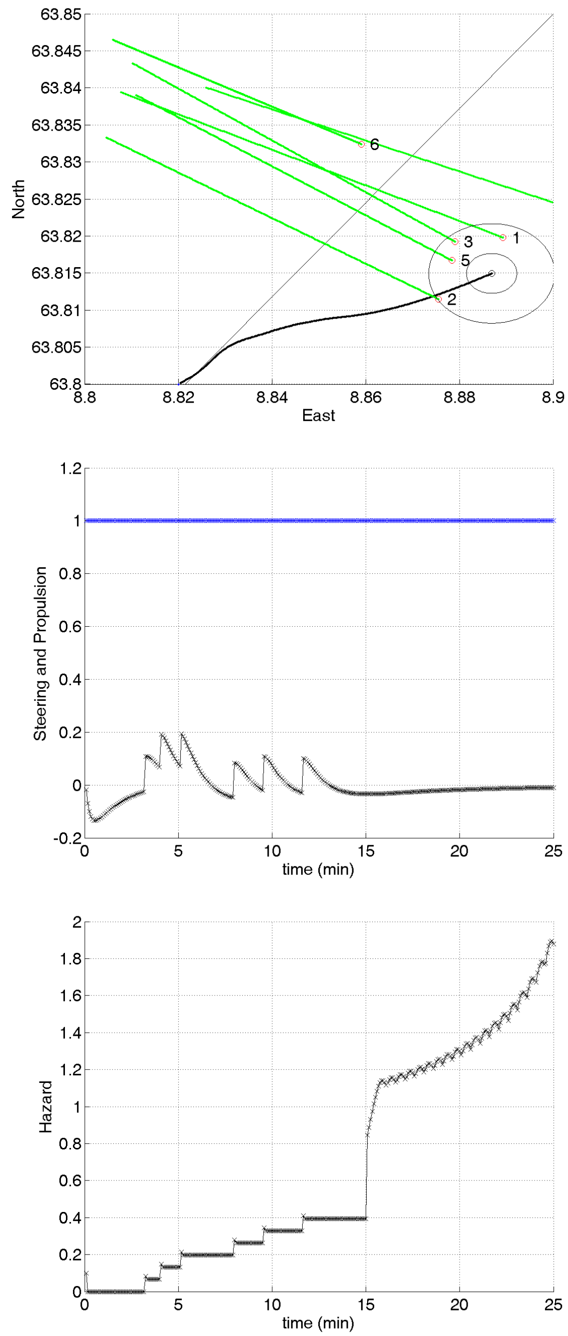

Fig. 10. Multiple obstacles crossing simulation, where own vessel has right to stay on.

in the simulation would have been given by a sequence of course offsets to cope with the course offset of the overtaking vessel, this resulting in a very unpredictable path. However, using the extended framework and taking into account in the predictions also the possible application of COLREGs by the other vessels, a smoother path is achieved by temporarily reducing the speed and then applying a single course offset.

D. Disturbances

Figure 14 illustrates a critical scenario: while the own vessel is overtaking a slower vehicle, two vessels are approaching from port side and other two vessel are approaching from starboard side. Moreover, a side-wind is assumed to blow at 5 m/s in the NW direction. In such overtaking and crossing scenario, the nominal algorithm would have commanded the ship to stop for a

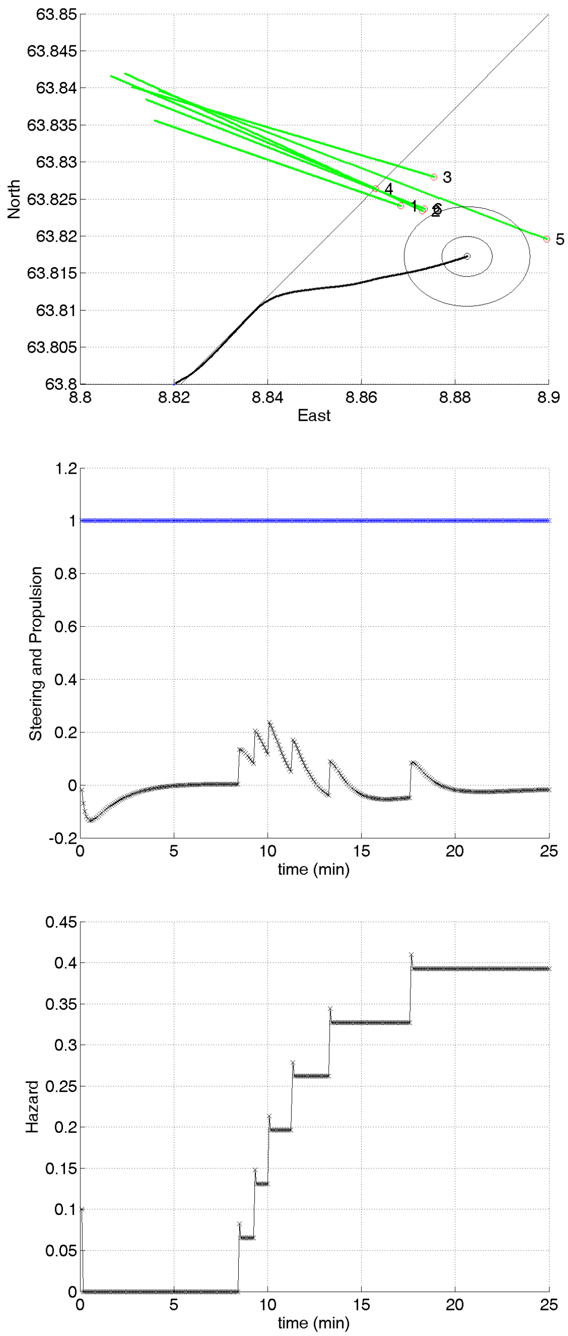

Fig. 11. Multiple obstacles crossing simulation, where own ship has right to stay on.

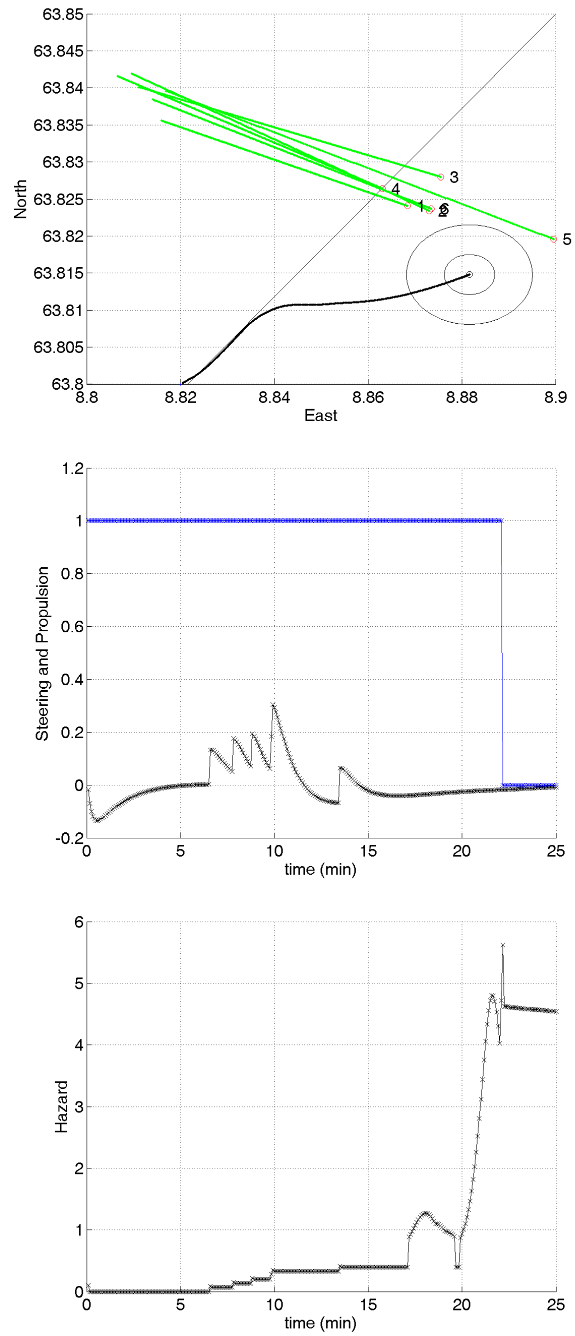

Fig. 12. Multiple obstacles crossing simulation, where own ship has right to stay on, with robustness enhancement.

sufficiently long amount of time. However, if one adopts the disturbance-sensitive algorithm introduced in Section IV-C, the action $P = 0$ is no longer considered safe due to possible drift, and the selected less-hazard scenario is instead characterized by two subsequent turns on the starboard side.

E. Obstacles with random motion

Finally, the case of obstacles moving along a random path is proposed in order to emphasize that, even if the vessel motion prediction is done on the basis of a straight trajectory, the method is still capable to successfully handle the presence of obstacles with nonlinear dynamics. Figures 15-19 illustrate some scenarios where the obstacles have random changes in speed and course.

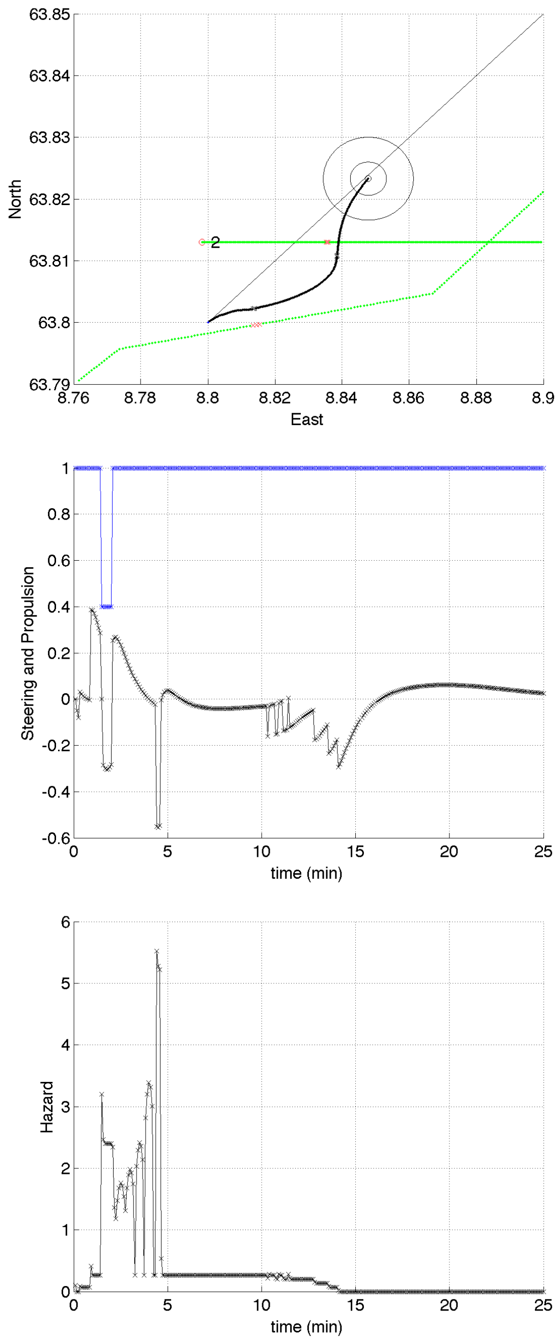

Fig. 13. Multiple obstacles crossing and head-on simulation, extended COLREGS-compliant framework.

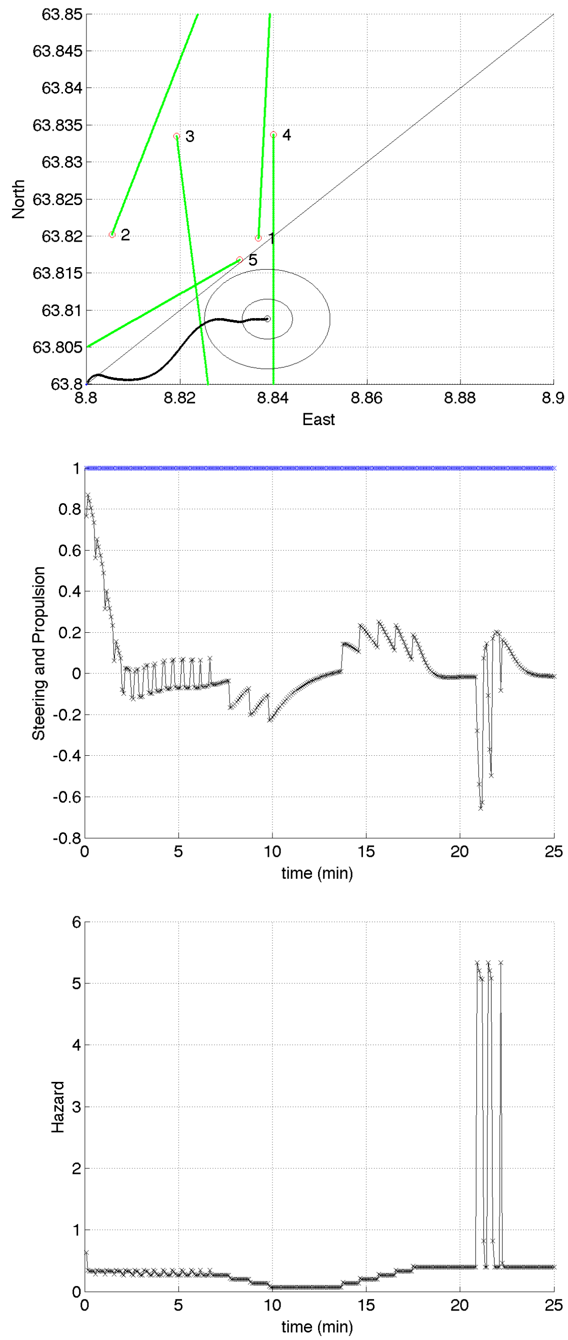

Fig. 14. Multiple obstacles with environmental disturbances evaluation

VI. Discussion

For situations with few obstacles, it seems to be sufficient to consider scenarios where there is no change in control behavior on the horizon. When the number of obstacles increase, the CAS would benefit from a more fine-grained set of control behaviors to choose from in order to find a smooth way out rather than making an emergency stop. Also, smaller safety margins could be possible with more scenarios.

There is an extensive set of tuning parameters and functions involved in the CAS. The algorithm can be tuned to exhibit a range of different priorities and behaviors by changing these parameters and functions. Tuning can be time-consuming as the tuning parameters are not completely independent.

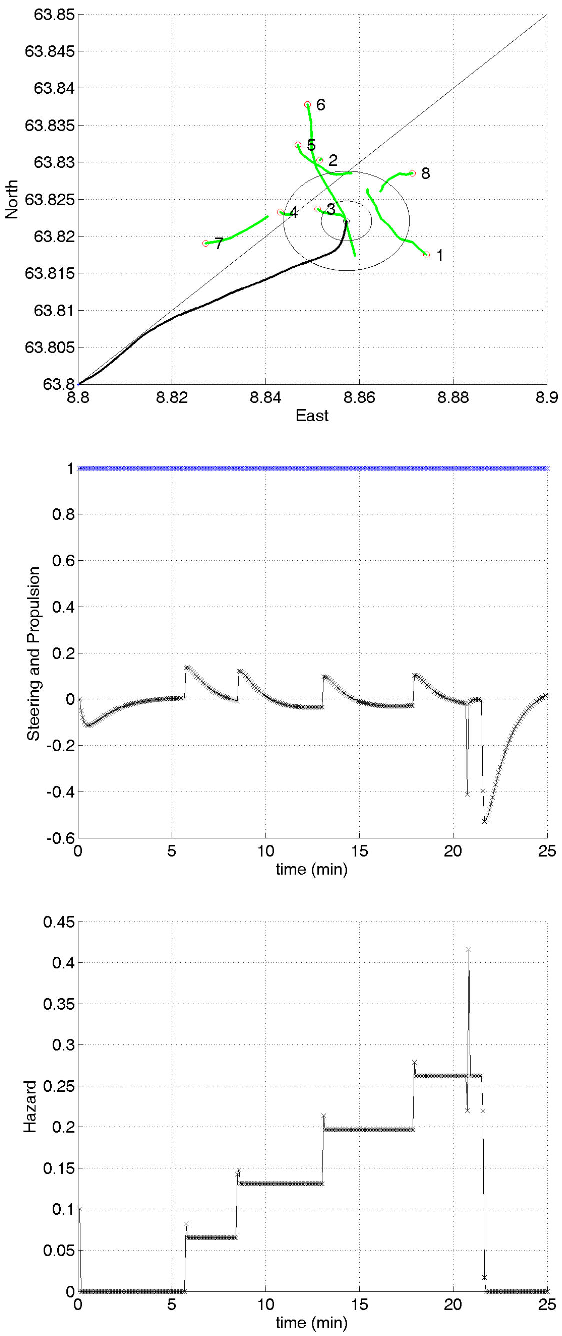

Fig. 15. Multiple obstacles making random changes in course and speed.

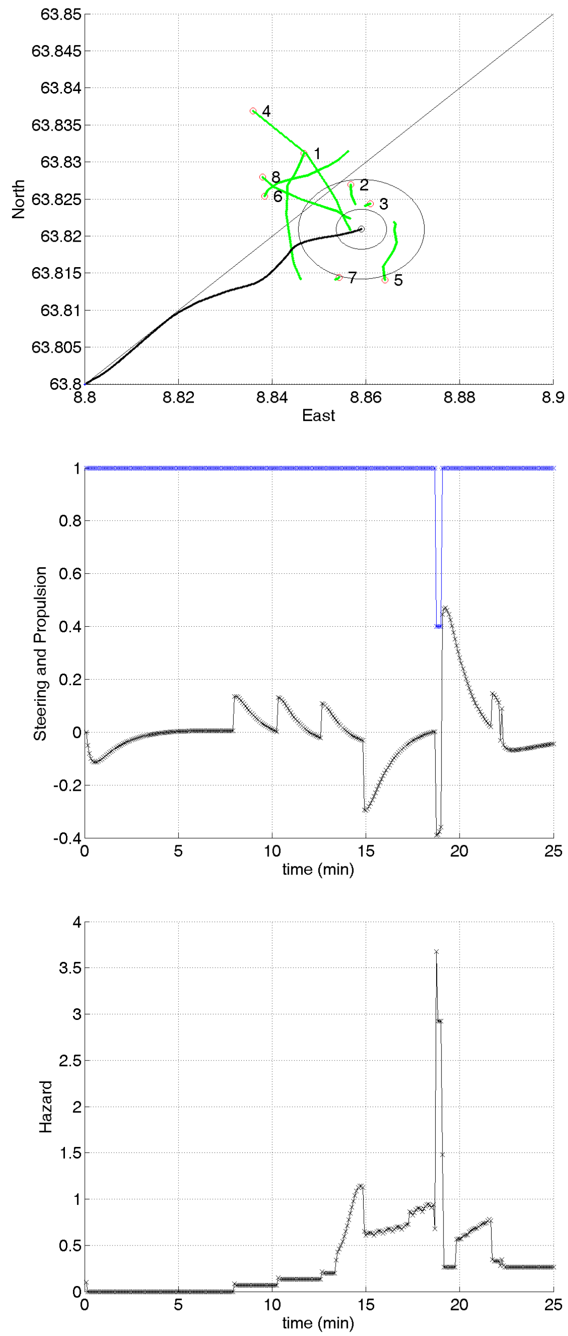

Fig. 16. Multiple obstacles making random changes in course and speed.

The presentation of the method and simulator has focused on the key/main rules of COLREGS, and we have not considered certain special cases such as narrow channels, traffic separation schemes, nor the modifications needed to operate in extreme weather conditions. We believe these extensions are relatively straightforward and can be managed by additional logic or dedicated selection of tuning parameters to use under such special conditions.

VII. Conclusions

Appendix

This section provides a brief overview of the main technical and operational requirements from COLREGs, [1], relevant for our purpose:

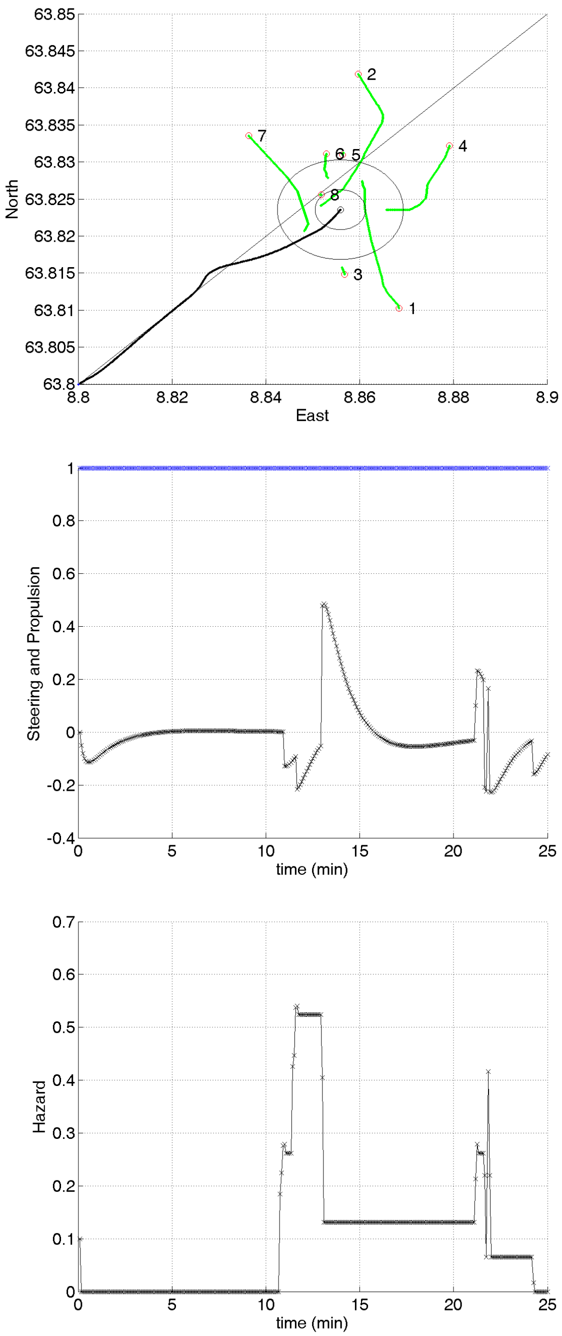

Fig. 17. Multiple obstacles making random changes in course and speed.

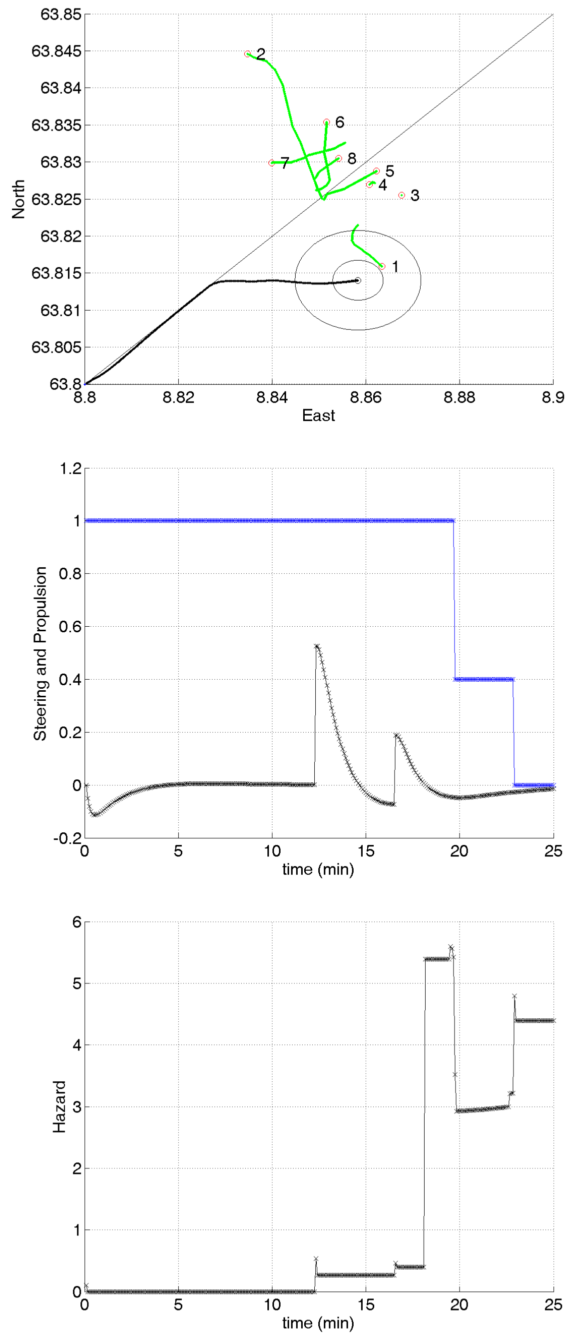

Fig. 18. Multiple obstacles making random changes in course and speed.

- **Rule 6 - Safe speed**. The following should be considered: Visibility, traffic density, stopping distance and turning ability, wind/waves/current, navigational hazards, draught vs. depth, radar/sensor state.
- **Rule 8 - Actions to avoid collision.** Actions shall be made in ample time. If there is sufficient sea-room, alteration of course alone may be most effective. Safe distance required. Reduce speed, stop or reverse if necessary. Action by the ship is required if there is risk of collision, also when the ship has right-of-way.
- **Rule 13 - Overtaking.** Any vessel overtaking any other shall keep out of the way of the vessel being overtaken. A vessel shall be deemed to be overtaking when coming up with another vessel

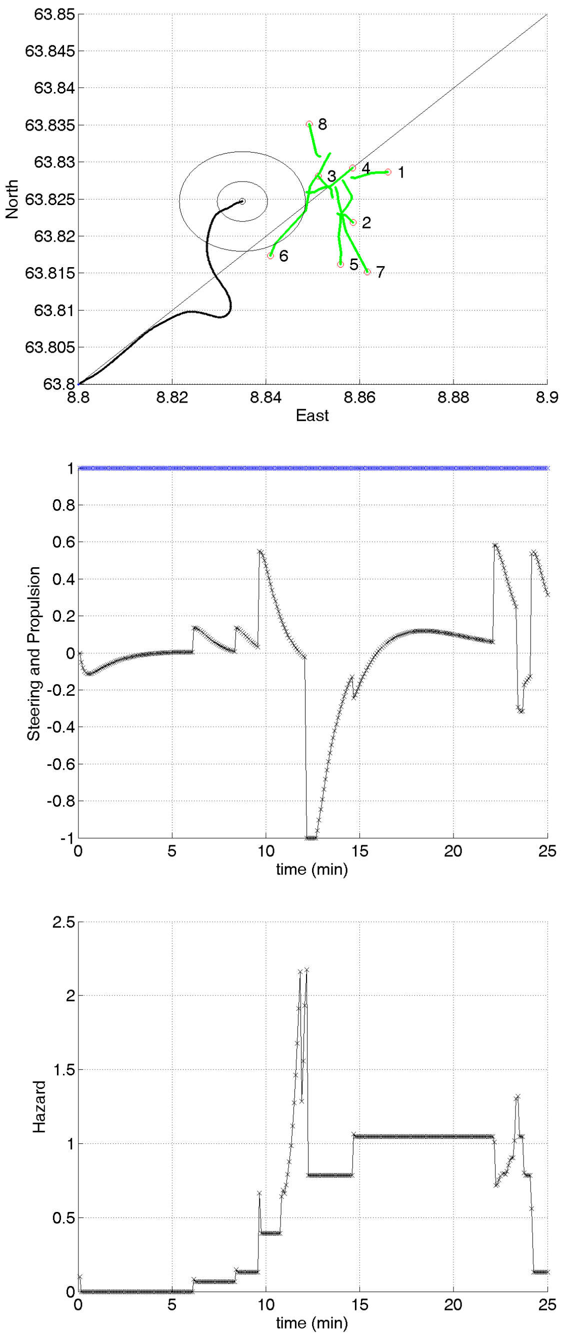

Fig. 19. Multiple obstacles making random changes in course and speed.

from a direction more than 22.5 degrees abaft her beam.

- **Rule 14 - Head-on situation.** When two power-driven vessels are meeting on nearly reciprocal courses so as to involve risk for collision, then alter course to starboard so that each pass on the port side of each other.
- **Rule 15 - Crossing situation.** When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way.
- **Rule 16 - Actions by give-way vessel.** Take early and substantial action to keep well clear.
- **Rule 17 - Actions by stand-on vessel.** Keep course and speed (be predictable) if possible. If it is necessary to take action, then the ship should try to avoid to alter course to port for a vessel on her own port side.
- **Rule 18 - Responsibilities between vessels.** Except for Rules 9, 10, and 13, a power-driven vessel shall keep out of the way of: a vessel not under command, a vessel restricted in her ability to manoeuvre, a vessel engaged in fishing, and a sailing vessel.
- **Rule 19 - Conduct of vessels in restricted visibility.** Avoid alteration of course to port for a vessel forward of the beam, and avoid alteration of course towards a vessel abeam or abaft the beam, if possible.

In addition, there are requirements for light and sound signals, as well as some rules that apply in special areas denoted as narrow channels and traffic separation schemes:

- **Rule 9 - Narrow channels.** Keep to starboard if possible. Vessels smaller than 20 meters, fishing vessels and sailing vessel shall not impede the passage of a ship that can only navigate in a narrow channel. Overtaking requires communication between the two vessels.
- **Rule 10 - Traffic separation schemes.** Stay in dedicated traffic lane. Leave traffic lanes at small angle. Avoid crossing if possible.

Acknowledgments

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