

Collaborative Collision Avoidance for Autonomous Ships Using Informed Scenario-Based Model Predictive Control

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Abstract: There exist several collision avoidance algorithms for autonomous ships. But the majority of them do not utilize information about other ships' intentions, except for observed position and velocity. As the attention for large-sized autonomous ships to be used in logistics is growing, autonomous ships will need to collaborate and negotiate with other ships to prevent reactive and agile collision avoidance maneuvers. As a first step towards a collaborative collision avoidance algorithm, we implemented a reactive short-range algorithm by utilizing other ships' trajectory plans. We aimed to improve the existing Scenario-Based Model Predictive Control (SB-MPC) algorithm by including route exchange-based trajectory predictions and called it the Informed SB-MPC. Additionally, we introduce adaptive and conditional parameter selection methods for the SB-MPC design. Hereby we implemented the compliance with the COLREGs Rule 18 concerning responsibility between vessels in addition to the existing Rules 13-17. The performance of the new method is demonstrated with head-on, crossing, overtaking, and multiple ships scenarios.

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1. INTRODUCTION

As a result of several studies carried out with small-sized autonomous ships over the years, it is now seen that larger-sized autonomous ships, i.e., the Maritime Autonomous Surface Ship (MASS), are becoming the center of attention. Autonomous ship-oriented logistics are believed to increase efficiency and decrease carbon footprint over truck-oriented land logistics. The European Union consortium AUTOSHIP (2019) project, Norwegian research-based innovation center SFI Autoship (2020), Danish non-profit innovation and project collaboration ShippingLab (2019), multi-national and multi-partner autonomous ship ecosystem ONE SEA (2016), DNV's zero-emission autonomous ship concept The Re-Volt (2013), Kongsberg Maritime-Yara collaboration zero-emission coastal container Yara Birkeland (Kongsberg Maritime, 2017), Kongsberg Maritime-ASKO collaboration autonomous barge (Kongsberg Maritime, 2020), the Nippon Foundation's Meguri 2040 (Nippon Foundation, 2022), Hyundai Heavy Industry's ocean crossing LNG carrier project (Maritime Executive, 2021) are examples of interesting developments in this field.

Regardless of size, autonomous ships need a collision avoidance system (CAS) that will enable them to avoid static and dynamic obstacles. For interested readers there are several comprehensive review articles on collision avoidance (CA) algorithms developed for autonomous ships, e.g., Öztürk et al. (2022), Vagale et al. (2021), Huang et al. (2020), Campbell et al. (2012). It is seen that the majority of algorithms make control decisions from the perspective of a single ship, and information exchange and collaboration between ships is not considered. However, it is important for large-sized ships to determine collision avoidance maneuvers collaboratively instead of relying on traffic rule compliance in combination with reactive methods that might entail bold maneuvers. The International Maritime Organization's (IMO) e-navigation and route exchange concepts also highlight the importance of collaboration between ships and shore units (IMO, 2018). EU-funded Sea Traffic Management (STM) Validation Project developed a standard format for the route exchange and proposed an amendment to IMO (IMO, 2021). Even though the proposed standard is intended for route plan exchange between ships and Vessel Traffic Services (VTS) and not for ship-to-ship collision avoidance, possible improvements in situational awareness especially with the MASS scenarios are identified in the document (IMO, 2021).

The relatively small number of existing studies on ship-to-ship collaborative collision avoidance for autonomous ships are reviewed by Akdağ et al. (2022). It is emphasized

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that the majority of the studies relied on iterative data exchange between autonomous ships and very few of them considered non-cooperative and conventional vessels in the scenarios. For MASS and conventional vessels to coexist, CA algorithms must comply with the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) (IMO, 1972). According to Burmeister and Constapel (2021), the COLREGs Rules 13-17 which explain head-on, crossing, overtaking scenarios, and stand-on, give-way responsibilities are intensively studied but Rule 18, responsibilities between vessels, is not covered widely. According to Rule 18, a power-driven ship shall keep out of the way of a ship that has a higher priority, e.g., restricted in maneuverability, constrained by her draught, engaged in fishing. This rule changes the power-driven ship's stand-on responsibility to give way so a MASS CA algorithm should take this rule into consideration.

Among the several CA algorithms, we will indicate a specific one since it is the basis of our work. Model Predictive Control (MPC) is a powerful control method that combines feedback control with dynamic optimization to find an optimal control action for each prediction horizon. MPC uses dynamic models for predicting future states and considers uncertainties, constraints, and objectives with a cost function to choose the optimal control action. Although MPC is widely used in the control of ground, aerial, and underwater vehicles, Johansen et al. (2016) are the first to implement it for COLREGs compliant ship collision avoidance. Later Hagen et al. (2018) introduced a transitional cost parameter to reduce oscillatory movements of the own ship and validated the scenario-based model predictive control (SB-MPC) algorithm at sea trials (Hagen et al., 2018; Kufalor et al., 2020). Tengesdal et al. (2020) included the probability of collision with nearby obstacles by using Monte Carlo Simulation with a Kalman Filter and named the algorithm as Probabilistic SB-MPC. Kjerstad (2020) utilized the other vessel's route information for trajectory prediction and compared the method with the original SB-MPC.

1.1 Contribution

Based on Johansen et al. (2016) and similar to Kjerstad (2020)'s approach, this study aims to improve the SB-MPC algorithm by including collaboration, i.e., information exchange between ships. We called the new algorithm Informed SB-MPC since the exchanged route information is utilized by the collision avoidance algorithm to predict other ships' future states but there is no further iterative steps to negotiate for an agreement. The exchanged information is assumed to contain trajectory plan and the COLREGs Rule 18 role. Trajectory plans are used for predicting other ships' intentions. While the original SB-MPC uses the straight-line prediction for the target ship's future states, this study introduces route exchanged-based trajectory prediction by utilizing waypoints and speed for the route leg. But at the same time, we introduced a supervisory control mechanism to convert back to straight-line prediction in case the target ship is not following its planned route. Additionally, the COLREGs Rule 18 is implemented with an additional term in the cost function and a new set of parameters. With the help of the COLREGs Rule 18 role, the own ship can change her responsibility from being a stand-on vessel to a give-way vessel according to the target ship's type of operation. We introduced

adaptive and conditional parameter selection methods to improve CAS performance and support flexibility for different scenarios. This study distinguishes itself from Kjerstad (2020) through contributions of a supervisory control mechanism, adaptive and conditional parameter selection, and the COLREGs Rule 18 implementation methods.

For the purpose of testing the proposed method, we prepared a simulation by considering some assumptions. We assumed the collaborating ships have communication systems. Noisy data, communication loss, or cyber security threats are not considered in the simulation. The scenarios are chosen in congested waters with grounding hazards and environmental forces are neglected to demonstrate the proof of concept rather than the control system's performance. The simulation is implemented in Python 3.8.4 language and run on a PC with ARM M1 8 Core 3200 MHz processor and 16 GB of LPDDR4 RAM. Ships are simulated as multiagent systems exchanging information over User Datagram Protocol (UDP) that simulates Automatic Identification System (AIS).

2. METHODOLOGY

2.1 Ship Model

A 3-degrees-of-freedom (DOF) ship maneuvering model presented in Eq. (1) is used to simulate the own ship dynamics (Fossen, 2021).

$$\begin{aligned} \dot{\boldsymbol{\eta}} &= \mathbf{R}(\psi)\boldsymbol{\nu} \\ \mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{D}(\boldsymbol{\nu})\boldsymbol{\nu} &= \boldsymbol{\tau} \end{aligned} \quad (1)$$

Here, $\boldsymbol{\eta} = (x, y, \psi)^T$ represents the ship's position and heading in the earth-fixed frame and $\boldsymbol{\nu} = (v_x, v_y, r)^T$ represents surge, sway velocities, and yaw rate in the body-fixed frame. The rotation matrix $\mathbf{R}(\cdot)$ is used to transform the states from body-fixed frame to earth-fixed frame. \mathbf{M} , $\mathbf{C}(\cdot)$, $\mathbf{D}(\cdot)$ are Inertia, Coriolis-centripetal, and Damping matrices respectively. The forces and moment applied in surge, sway directions, and yaw axis are represented by $\boldsymbol{\tau}$. The wind, wave, and ocean current forces are not considered in this study, without loss of generality, so they are not included in the simulation.

The ships follow their route plans with the Line-of-Sight (LOS) guidance principle (Fossen, 2021). The LOS guidance calculates a course command (χ_{LOS}) by waypoint information, a predefined look-ahead distance, and the cross-track distance values. A smaller look-ahead distance causes the ship to track its planned path with more agile turns and the cross-track distance represents the closest distance between the ship and its path. The collision avoidance system (CAS) calculates a course offset value χ_{ca} , i.e., the amount of change from the ship's course. We can calculate the desired course command χ_c by combining χ_{LOS} and χ_{ca} values. Similar to χ_{ca} , the CAS calculates a surge speed offset value u_{ca} . We can calculate the desired surge speed u_c by combining the planned surge speed u_d and the speed offset u_{ca} . In this study, a feedback linearizing controller for surge speed and a proportional controller for the heading is used for calculating desired forces and moments which will be applied by the thrusters. In an effort to design a CAS for bigger ships, a 116 meters long Platform Supply Vessel (PSV) model parameters from Minne (2017) are chosen both for the own ship and target ships in the simulation example in this article.

2.2 Informed Scenario-Based Model Predictive Control

In a similar way to Johansen et al. (2016), we defined a finite set of control actions to represent offsets from the course (χ_{ca}) and propulsion commands (u_{ca}). The course offset values of $-90, -75, -60, -45, -30, -15, 0, 15, 30, 45, 60, 75, 90$ degrees and speed offset values of keep speed, slow forward, and stop are chosen both to decrease the computational demand for numerical optimization and to demonstrate observable maneuvers for other ships. This finite set of control actions results in 39 combinations to be solved with a cost function at every defined time step. The proposed cost function, i.e., hazard evaluation function, is presented in Eq. (2) and contains collision cost, risk factor, COLREGs compliance, maneuvering penalty, and grounding penalty. It is similar to Johansen et al. (2016) except evaluation method for COLREGs rule violation and new additional terms for COLREGs Rule 18 implementation, and grounding.

$$\mathcal{H}^k(t_0) = \max_i \max_{t \in D(t_0)} (C_i^k(t) \mathcal{R}_i^k(t) + \kappa_i \mu_i^k(t) + \rho_i \zeta_i^k(t)) + f(u^k, \chi_{ca}^k) + \gamma \mathcal{G}^k(t) \quad (2)$$

$C_i^k(t)$ is presented in Eq. (3) and it is the cost associated with collision with target ship i at time t in scenario k . $C_i^k(t)$ is calculated by relative velocities of own ship ($\mathbf{v}_0^k(t)$), target ship ($\mathbf{v}_i^k(t)$) which are velocities on x and y axis. Tuning parameter K_i^{coll} which depends on target ship's type, target ship's size, own ship's right to stay on, or responsibility to keep away from target ship's course.

$$C_i^k(t) = K_i^{\text{coll}} \|\mathbf{v}_0^k(t) - \mathbf{v}_i^k(t)\|^2 \quad (3)$$

The collision risk factor $\mathcal{R}_i^k(t)$ is presented in Eq. (4) and it is derived from instantaneous distance between ships ($d_{0,i}^k(t)$), safety distance parameter (d_i^{saf}), difference between the time of prediction (t) and current time (t_0).

$$\mathcal{R}_i^k(t) = \begin{cases} \frac{1}{|t - t_0|^p} \left(\frac{d_i^{\text{saf}}}{d_{0,i}^k(t)} \right)^q, & \text{if } d_{0,i}^k(t) \leq d_i^{\text{saf}} \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

A smaller distance between ships increases the collision risk factor. Time difference enables for decreasing the risk factor for the more distant predictions. p and q values are exponential tuning parameters. $\mu_i^k(t)$ is the binary cost for the COLREGs violation and κ_i is the tuning parameter. In this study, the binary value for the COLREGs violation is calculated differently than Johansen et al. (2016). We used the threshold angle values from Woerner (2016) and relative bearings of ships to define the COLREGs head-on, crossing, and overtaking rules. The logic expressions to derive $\mu_i^k(t)$ is given by

$$\begin{aligned} \mu_i^k(t) &= R13 \vee R14 \vee R15 \\ R13 &= OG \wedge |\beta_i| < 22.5^\circ \\ R14 &= HO \wedge \beta_i < 13^\circ \\ R15 &= ((CR_{GW} \vee CR_{SO}) \wedge \beta_i \leq 0^\circ) \vee \neg ON \end{aligned} \quad (5)$$

where binary indicators $OG, ON, HO, CR_{GW}, CR_{SO}$ represents overtaking, overtaken, head-on, crossing give-way, crossing stand-on rules, and β_i represents the relative bearing of the target ship i from the own ship as in Fig. 1.

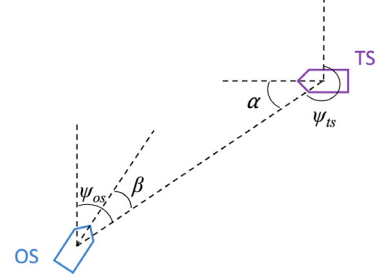


Fig. 1. A diagram for ship poses where OS and TS represent ownship and targetship, ψ_{os} and ψ_{ts} represent ship headings, β and α represent relative bearings.

$\zeta_i^k(t)$ is a new term to implement the COLREGs Rule 18. This additional term is presented in Eq. (6) and is taken into account in cost calculation if the target ship shares her Rule 18 priority, i.e, not under command, restricted in maneuverability, constrained by draught, engaged in fishing, sailing, or power-driven.

$$\zeta_i^k(t) = \begin{cases} m, & \text{if } |\beta_i| \leq 22.5^\circ \vee |\alpha_i| \leq 22.5^\circ \\ n, & \text{if } 22.5^\circ < |\alpha_i| \leq 90^\circ \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

$\zeta_i^k(t)$ with the weight parameter ρ_i are used for the power-driven MASS to comply with Rule 18 and to keep out of higher priority target ship's way. α_i represents the relative bearing of the own ship from the target ship i and is illustrated in Fig. 1. m and n represent penalty values and we used $m = 1.1$ and $n = 1$ respectively. The penalty function in Eq. (7) describes the cost of own ship's deviation from her course and speed.

$$f(u, \chi_{ca}) = k_u(1 - u_{ca}) + k_\chi \chi_{ca}^2 + \Delta_u |u_{ca} - u_{last}| + \Delta_\chi (\chi_{ca} - \chi_{last})^2 \quad (7)$$

Here, $u_{ca}, u_{last}, \chi_{ca}, \chi_{last}$ represent propulsion offset, last propulsion offset, course offset, and last course offset commands respectively. k_u and k_χ penalize changes from nominal speed and course. Δ_u and Δ_χ are used to influence deviations from previous commands. k_χ and Δ_χ both have two different sets of parameters for port and starboard course offsets. Bigger values are chosen for $k_{\chi, port}$ and $\Delta_{\chi, port}$ to encourage compliance with the COLREGs Rules 14, 15, and 17. We applied a similar method to the collision risk factor function for calculating the grounding risk. The grounding penalty function $\mathcal{G}^k(t)$ is presented in Eq. (8) and d_{static}^k represents the closest distance to a static obstacle polygon for scenario k . p_g, q_g are exponential tuning parameters for the influence of future predictions on the risk of grounding.

$$\mathcal{G}^k(t) = \begin{cases} \frac{1}{|t - t_0|^{p_g}} \left(\frac{d_{static}^{\text{saf}}}{d_{static}^k(t)} \right)^{q_g}, & \text{if } d_{static}^k(t) \leq d_{static}^{\text{saf}} \\ 0, & \text{otherwise} \end{cases} \quad (8)$$

2.3 Route Exchange-Based Trajectory Prediction

Johansen et al. (2016) and Hagen et al. (2018) used straight-line predictions for target ship's future states in the prediction horizon. In addition to the straight-line prediction, we implemented a route exchange-based trajectory

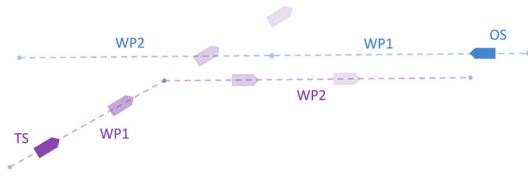


Fig. 2. Comparison of straight-line and route exchange-based trajectory predictions for target ship.

prediction similar to Kjerstad (2020) to use target ship's intention for improving navigational safety. Assuming the target ship's trajectory plan is shared through a communication system, the own ship can predict the target ship's future states depending on course angles derived from consecutive waypoints and the speed value defined for the route leg. The future trajectories can be calculated by using Eq. (9).

$$\begin{aligned}\hat{x}_i(t) &= x_i(t_0) + U_i(t_0)\cos(\chi_i(t_0))(t - t_0) \\ \hat{y}_i(t) &= y_i(t_0) + U_i(t_0)\sin(\chi_i(t_0))(t - t_0) \\ U_i(t_0) &= \sqrt{v_{x_i}(t_0)^2 + v_{y_i}(t_0)^2}\end{aligned}\quad (9)$$

Fig. 2 gives an example of a situation where route exchange-based trajectory prediction is more advantageous over the straight-line prediction. However, it would not be correct to blindly assume that the route plan will be followed by the target ship. That is the reason for implementing a supervisory control mechanism to monitor whether the target ship is following its planned route. According to STM (2019), the route exchange messages will contain a cross-track distance (XTD) value. The XTD value tells us how much deviation the target ship can have on her planned route. For this study, we set 100 meters for the XTD threshold value and convert back to the straight-line prediction model if the target ship deviates more than 100 meters from her planned route. Although the supervisory control mechanism is applied in the simulation, comparative results were not presented with the intention of not increasing the article size.

2.4 Adaptive and Conditional Parameter Selection

Parameter selection and tuning must be done cautiously for the SB-MPC to yield safe and COLREGS-compliant control actions. Longer prediction horizon and larger safety distance values may be selected, especially when large ships are involved. But longer prediction horizon requires more computational power which can cause less frequent optimization. To implement the SB-MPC to larger ships, we chose 2000, 1800, 500 meters for initializing, close, and safety distances respectively. A prediction horizon of 600 seconds is chosen for future predictions while the algorithm repeats every 5 seconds. To increase the distance from the target ship one can suggest choosing a larger safety distance. Larger lateral distances in head-on scenarios may not be proper, especially in congested waters. A larger safety distance causes the own ship to act earlier and start an evasive maneuver from an overtaking ship. We proposed a safety distance calculation based on the target ship's relative bearing angle to both use a larger safety distance and prevent the mentioned problems. Dynamic safety distance calculation is presented in Eq. (10).

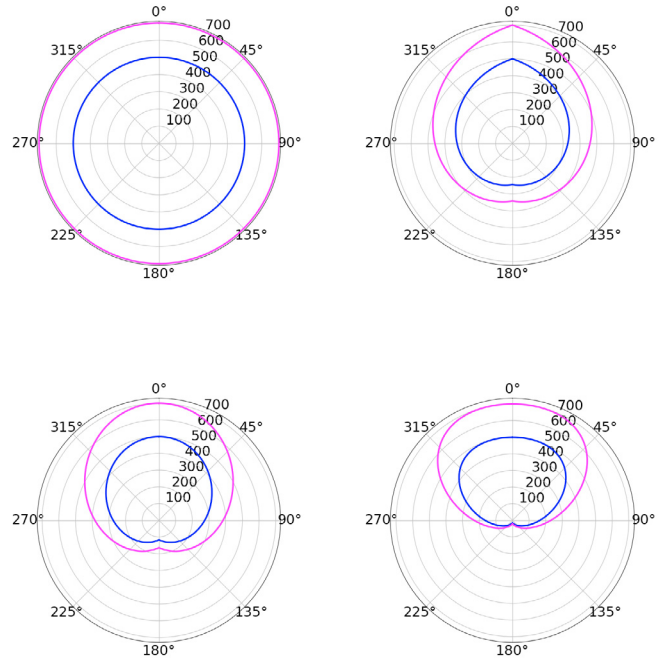
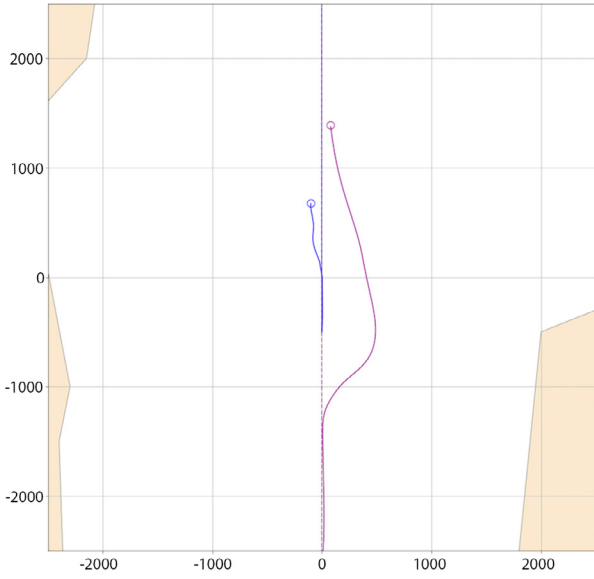


Fig. 3. Safety distance variations. (a) Circular safety distance (b) Relative bearing-based safety distance (c) Second power of relative bearing-based safety distance (d) Fourth power of relative bearing-based safety distance. The outer areas in the figures represent the safety distance based on COLREGs Rule 18 condition and inner areas are for default scenarios.

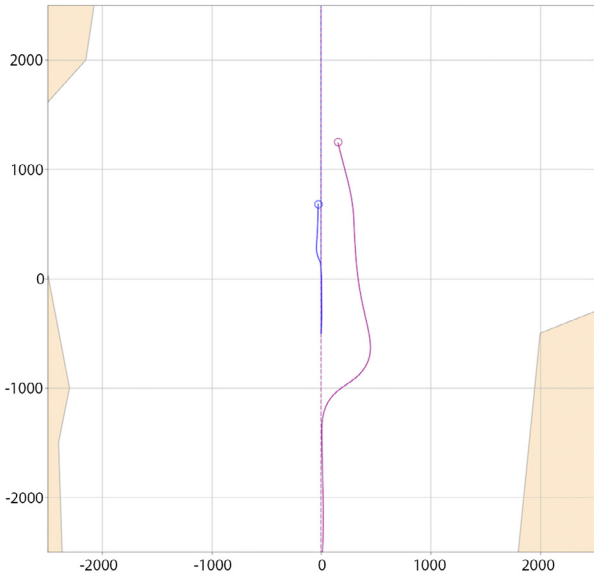
$$d_i^{safe} = \frac{c_{dist}}{|\beta_i|^k + l} \quad (10)$$

where c_{dist} represents a constant value and β_i represents the relative bearing of the target ship i . We used k and l parameters to deform the safety distance according to our objective. As in Fig. 3, a circular safety distance changes to a droplet geometry if c_{dist} is divided by the target ship's relative bearing. Dividing c_{dist} with increased powers of the relative bearing influences to have more distance at fore than aft direction. A lower value of l helps to squeeze the safety distance from port and starboard while increasing the distance at the bow-stern directions. The consequences of choosing adaptive safety distance can be observed from Fig. 4 where the own ship is overtaken by a target ship. Fig. 3a shows that the own ship starts an earlier evasive maneuver if a circular safety distance is used. If the parameter tuning process is improved, an even more stable overtaken scenario can be achieved by the adaptive safety distance calculation, as seen in Fig. 3b.

In addition to the adaptive parameter selection, we suggested that we can also change the parameters depending on conditions. For example, if the target ship is not under command, restricted in maneuverability, constrained by her draught, engaged in fishing, or a sailing vessel the COLREGs Rule 18 requires that the own power driven ship shall keep out of the other ship's way. In this case, the existing parameter set can lead to dangerous results in crossing scenarios where the own ship is in the stand-on role. The own ship, which is in the stand-on role, waits for



(a) Overtaken with a circular safety distance



(b) Overtaken with the safety distance based on the second power of relative bearing

Fig. 4. Effects of the new safety distance calculation on overtaking scenario. Purple ship is overtaking blue ship while both ships have the same collision avoidance algorithm. Colored circles represent current ship positions. Constant and dashed lines represent past and planned trajectories respectively.

the target ship to start an evasive maneuver until the cost value is high enough to start her own evasive maneuver.

The parameter set used in the SB-MPC is $P = \{d^{init}, d^{close}, d^{safe}, k_u, \Delta_u, k_{\chi, port}, k_{\chi, stb}, \Delta_{\chi, port}, \Delta_{\chi, stb}, \kappa, \rho, K^{coll}, p, q, p_g, q_g, \gamma\}$. We defined two sets of parameters, i.e., $P_{default}$ and P_{R18} . $P_{default}$ is used if the target ship is a power driven vessel (PDV) and P_{R18} is used if the target ship has a higher priority condition:

$$P = \begin{cases} P_{default}, & \text{if TS} = \text{PDV} \\ P_{R18}, & \text{if TS} \neq \text{PDV} \end{cases} \quad (11)$$

Conditional parameter selection can be used with multiple ships with different COLREGs priorities. The algorithm evaluates each target ship individually and selects the relevant parameter set to calculate a cost value for choosing optimal control inputs. A multiple-target ships scenario with only one of them having higher Rule 18 priority is presented later in the results.

3. RESULTS

We observe from simulations that the Informed SB-MPC algorithm can give advantageous results compared to the classical algorithm, depending on the selected tuning parameters, position, and speed differences between the ships. In Fig. 5 we presented the results from a head-on scenario where the target ship has a planned port turn. As seen from the figure if the ships are not utilizing the route exchange messages, the own ship starts a starboard turn to comply with the COLREGs. But if the own ship knows the target ship's planned trajectory, then it would initiate a port turn.

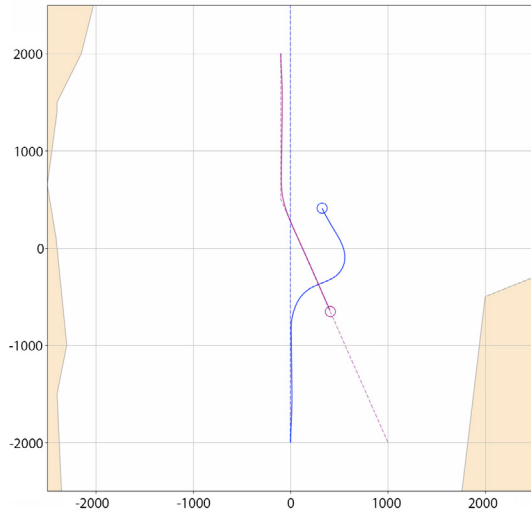
A similar result can be observed from a crossing give-way scenario in Fig. 6. Instead of unnecessary starboard turn to comply with the COLREGs, the own ship continues and regulates its distance with the target ship if it uses the route exchange information.

For the crossing stand-on scenario, we chose a target ship with a COLREGs Rule 18 priority, e.g., a vessel restricted in her maneuverability or engaged in fishing. As seen from Fig. 7, if the target ship's Rule 18 priority information is not used, the own ship assumes the target ship will give way according to the COLREGs Rule 15. The own ship continues and passes in front of the target ship with a small distance. Once the conditional parameter selection is used, the own ship acknowledges the target ship's priority and reduces its speed to keep out of her way.

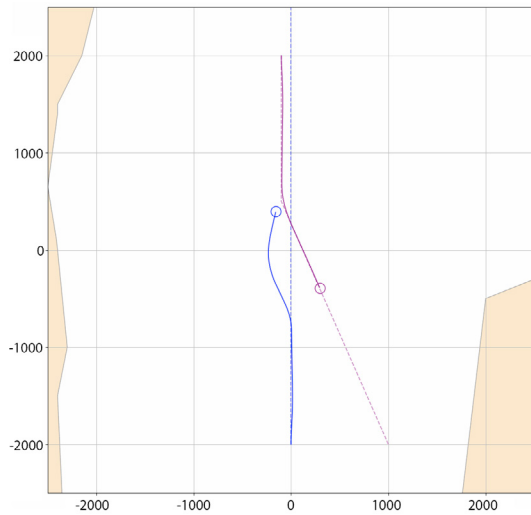
Finally, in order to test the algorithm's performance, a multiple ships scenario is simulated with three ships. As seen in Fig. 8, one of the ships has a COLREGs Rule 18 priority and the others are power-driven vessels with the proposed CAS. While the high priority ship continues with constant speed and course, others regulate their speeds and courses to both comply with the COLREGs and avoid the collision.

4. DISCUSSION

The proposed algorithm is called Informed SB-MPC because the ships use the exchanged information for optimal control but the algorithm is not capable of further negotiation. For example, in Fig. 5 and Fig. 6, autonomous ship's COLREGs non-compliant intention should be acknowledged by other ships in case they decide to start COLREGs compliant maneuvers that can result close encounters. Therefore, we plan to improve this method by including an interactive negotiation protocol in our future studies. Informed SB-MPC algorithm is a reactive and short-range collision avoidance method even though the behavior of large ships is considered in parameter selection. We believe with negotiation and collaboration capability, ships can interact at longer distances and make proactive and less effortful maneuvers to prevent collision. In this way, the Informed SB-MPC can be used as the last line-of-defense for unpredictable situations and non-cooperative vessels. The most laborious process of the SB-MPC algorithm design is to tune parameters that can give good results in



(a) Head-on scenario result without the route exchange capability.

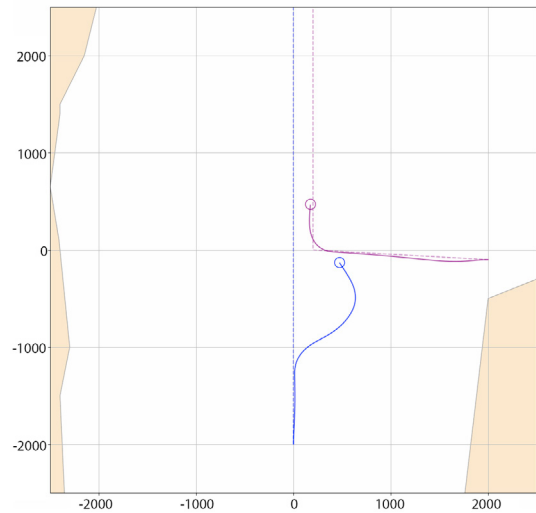


(b) Head-on scenario result with the route exchange capability.

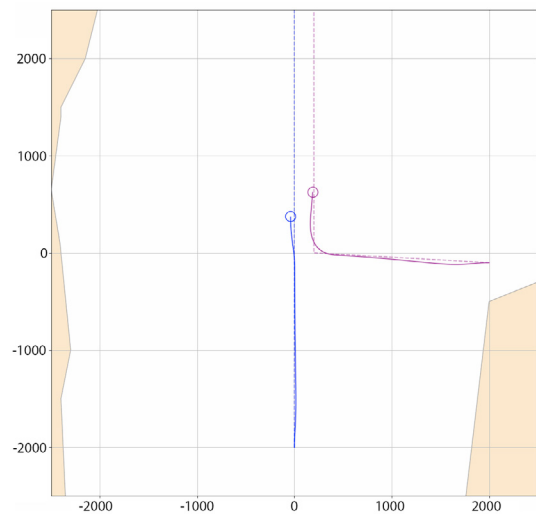
Fig. 5. Comparison of head-on scenarios. Blue ship, i.e. OS, is the autonomous ship with collision avoidance algorithm and the purple ship is the TS that follows its trajectory. Colored circles represent current ship positions. Constant and dashed lines represent past and planned trajectories respectively.

different scenarios. The parameters selected in this study were obtained as a result of testing different scenarios with lengthy efforts. However, even if the algorithm produces satisfactory results that do not violate the safety distance for randomly selected scenarios, it is not always guaranteed that the own ship movements will be similar to the traditional navigational behaviors. Therefore, the need of applying a systematic validation method after parameter tuning is evident here. The systematic validation method should include both batch and edge tests, the first refers to the selection of countless random scenarios and the second refers to the selection of specific problematic scenarios.

As an idea for future studies, a machine learning model can be designed that will adaptively estimate parameters over a data set to be created using different scenarios. Additionally, reconsidering the existing cost function and defining it to contain fewer parameters may also be a solution to the tuning problem of the SB-MPC algorithm.



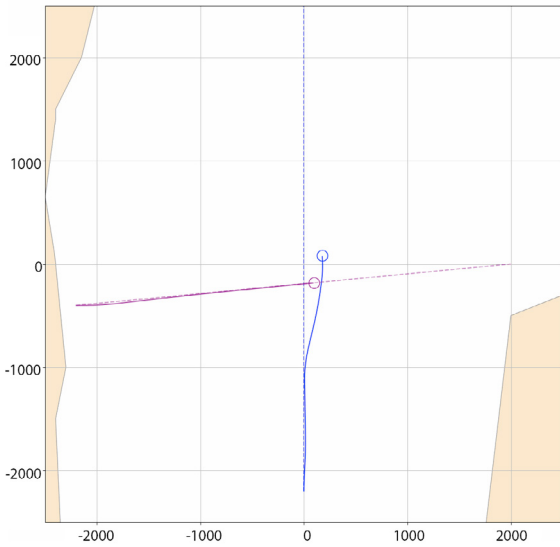
(a) Crossing give-way scenario result without the route exchange capability.



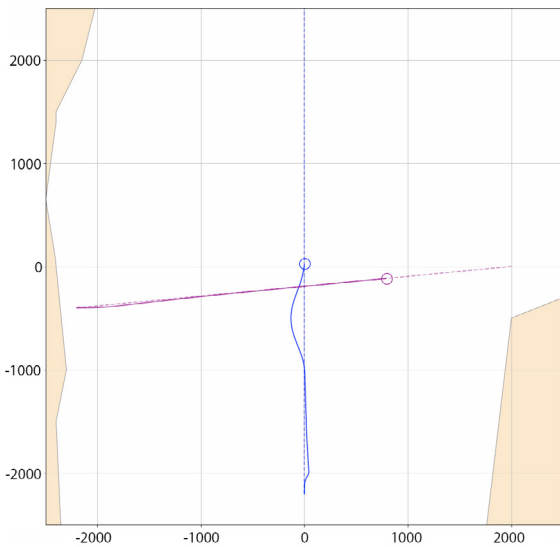
(b) Crossing give-way scenario result with the route exchange capability.

Fig. 6. Comparison of crossing give-way scenarios. Blue ship, i.e. OS, is the autonomous ship with collision avoidance algorithm and the purple ship is the TS that follows its trajectory. Colored circles represent current ship positions. Constant and dashed lines represent past and planned trajectories respectively.

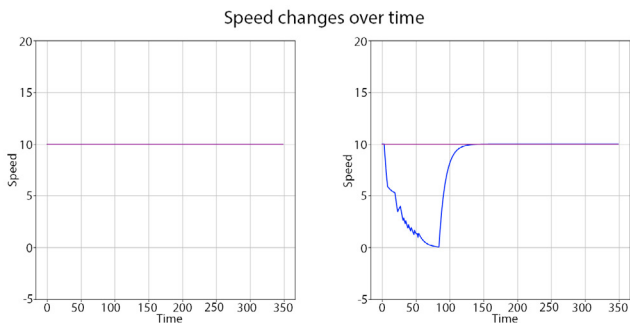
The ship type needs to be communicated to other ships by navigational lights and shapes, VHF radio, or AIS in order to determine the degree of priority among ships according to the COLREGs Rule 18. Ship type and special maneuvers can be broadcasted with AIS, but this information needs to be submitted to the device manually by an operator. A previous study shows that a significant number of ships are transmitting wrong or outdated static data (Harati-Mokhtari et al., 2007). To utilize the conditional parameter selection of the Informed SB-MPC, we assumed the ships are sharing up-to-date ship type information. But it is evident that the own ship will need a reliable ship classifier to identify the target ship's type.



(a) Crossing stand-on scenario result with default parameters.

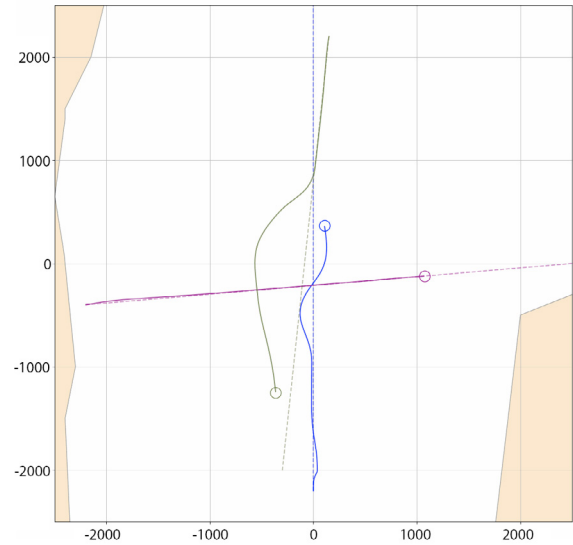


(b) Crossing stand-on scenario result with the COLREGs Rule 18 parameters.

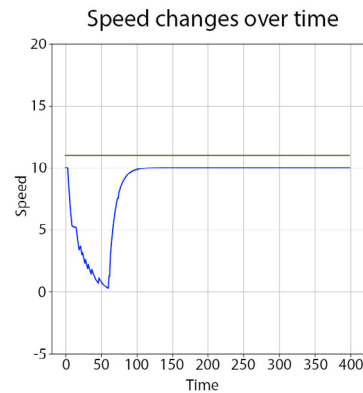


(c) The comparison of speed changes, the figure on the left with the default parameters and the right with the Rule 18 parameters.

Fig. 7. Comparison of crossing stand-on scenarios. Blue ship, i.e. OS, is the autonomous ship with collision avoidance algorithm and the purple ship is the TS with a COLREGs Rule 18 priority. Colored circles represent current ship positions. Constant and dashed lines represent past and planned trajectories respectively.



(a) Multiple ships encounter scenario. Blue and green ships are power driven while purple ship is restricted in her maneuverability.



(b) Speed changes for multiple ships scenario.

Fig. 8. Multiple ships encounter scenario. Blue and green ships are power-driven vessels with collision avoidance algorithm and the purple ship has a COLREGs Rule 18 priority. Colored circles represent current ship positions. Constant and dashed lines represent past and planned trajectories respectively.

5. CONCLUSION

In this study, we introduced a reactive collision avoidance algorithm by utilizing other ships' trajectory plans. We aimed to improve the existing SB-MPC algorithm by including route exchange-based trajectory predictions, adaptive and conditional parameter selection methods, and implementation of the COLREGs Rule 18, responsibility between vessels. We called the algorithm Informed SB-MPC since the ships use the exchanged information for optimal control but the algorithm is not capable of further negotiation. As a result, this study is the first step of a future collaborative collision avoidance algorithm which will be for medium ranges and covers negotiation capability.

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