Intent inference-based ship collision avoidance in encounters with rule-violating vessels

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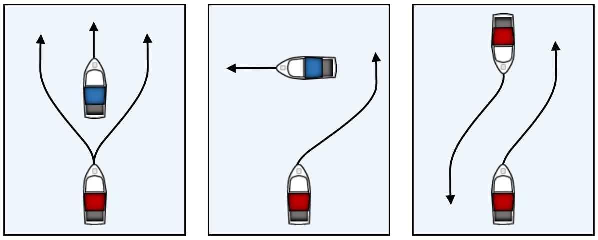
***Abstract*— All vessels operating in a marine environment are required to comply with the international regulations for preventing collisions at sea (COLREGs), which provide the guidelines and evasive procedures required to resolve potential conflicts between vessels. However, not all vessels strictly abide by COLREGs, often leading to dangerous situations. This paper presents a novel approach for robust collision avoidance in encounter situations involving COLREG-violating vessels. A probabilistic velocity obstacle algorithm based on intent inference is designed and implemented with consideration of the tradeoff between the adherence to traffic rules and the proactive evasive actions for safety. One-to-one and multi-ship encounter situations in the presence of rule-violating vessels are examined through Monte-Carlo simulations, and the results are discussed to demonstrate the feasibility and performance of the proposed approach.**



(a) Overtaking (b) Crossing (c) Head-on

Fig. 1. Compliant evasive procedures defined in COLREGs. Red ships take an evasive maneuver (give-way) whereas blue ships maintain their course and speed (stand-on).

I. INTRODUCTION

In recent years, autonomous surface vessels (ASVs) have been attracting increasing research attention worldwide. Because ASVs will operate in the same water space as conventional manned vessels, it is necessary for them to sense and avoid other vessels while obeying maritime traffic rules. For collision avoidance, all vessels must comply with the international regulations for preventing collisions at sea (COLREGs), which provide the evasive procedures in three encounter situations: overtaking, head-on, and crossing, to ensure safe conflict resolution [1]. Figure 1 shows the illustration of compliant evasive procedures in each encounter situation. The figure shows that at least one vessel must avoid the other vessel; thus they can safely resolve this situation.

Many researchers have developed COLREG-compliant collision avoidance algorithms for ASVs. The rapid-exploring tree (RRT) has been modified to the COLREG-RRT for satisfying the COLREGs [2]. A changeable action space approach, which branches the possible path and finds a solution using A*, was developed, and its performance was verified through sea trials [3]. A behavior-based robot can divide a complex problem into small sub-problems using multiple behaviors [4], and this concept was applied to automatic ship-collision avoidance [5]. The velocity obstacle (VO) is used to resolve conflicts with multiple moving obstacles, and researchers in the maritime domain have exploited this feature to perform COLREG-compliant maneuvers [6]. The VO with the worst-case uncertainty (WVO) [7], dynamic reciprocal VO (DRVO) [8], generalized VO (GVO) [9], and fast probabilistic VO (fPVO) [10] are extensions of the VO approach for application in the maritime domain with consideration of the COLREGs. Owing to recent improvements in computation power, model predictive control (MPC) has been used to solve ship-collision avoidance problems. The ship domain approach involves the use of branching-course MPC for generating COLREG-compliant paths, as described in [11]. Similarly, MPC with a discretized finite set of control behavior was applied for collision avoidance in [12], and the performance of the algorithm was evaluated using sea trials involving an ASV [13]. Nonlinear MPC-based collision avoidance considering the nonlinearity of ship dynamics was proposed in [14]. Additionally, various approaches for generating COLREG-compliant paths, such as by using deep-Q learning (DQN) [15], a dynamic window [16], a virtual force field [17], an adaptive-network-based fuzzy inference system (ANFIS) [18], and fuzzy logic [19], have been proposed.

However, in real-world maritime traffic situations, surrounding vessels do not always strictly follow the COLREGs. Such violations are even more threatening, and the COLREGs do not offer appropriate solutions in these circumstances. Therefore, the vessels must proactively predict other vessels' rule violations and undertake appropriate actions during encounters with COLREG-violating vessels. For quantifying the COLREG violation/compliance of traffic ships, case law was used to supplement the content absent from the COLREGs [20]. In [21], the Douglas-Peucker (DP) algorithm for trajectory representation and the nonlinear

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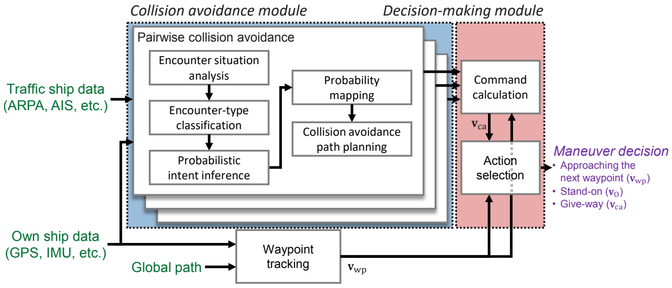


Fig. 2. Overall procedure for intent inference-based autonomous ship navigation: the blue box denotes the collision avoidance module, and the red box represents the decision-making module.

VO (NLVO) were used to estimate the intention of the give-way vessel for the stand-on vessel's situational awareness. To determine the amount of time needed for the stand-on vessels to take evasive action, the stage of the evasive procedure is defined, and the start time of each stage is calculated with consideration of the ship dynamics [22]. Without estimating intention, the sharing intention is proposed for another solution to relax COLREG-specified constraints [23]. However, none of the existing studies focused on developing a systematic decision-making procedure based on intent inference for automated collision avoidance under the presence of rule-violating vessels.

This paper presents a systematic avoidance procedure against other vessels' COLREG violations, as an extension of the author's previous studies [10], [24]. In [24], we focused on inferring the opponent ship's rule violation according to the sensing capability of the own ship. However, a collision avoidance procedure to respond to rule-violating ships was not discussed. In [10], on the other hand, a collision avoidance technique was proposed, but the other ship's intention including rule violation was not considered. These earlier studies are extended and reformulated to explicitly address the decision making when rule-violating vessels are present in this study. Firstly, in order to apply the inference result to collision avoidance, the inference result is used as the parameter for quantifying the required amount of rule compliance and avoidance. Additionally, the reciprocal fast probabilistic VO (R-fPVO), which incorporates the concept of the reciprocal VO (RVO) [25] with the fPVO [24], is proposed to select an evasive action. The proposed procedure can be used to calculate appropriate actions to deal with the encounters with COLREG-violating vessels as well as COLREG-compliant vessels. The performance of the proposed approach is verified using ship traffic simulations including cases of one-to-one encounters and multi-ship encounters.

II. PROPOSED ALGORITHM

Figure 2 presents the overall procedure of intent inference-based collision avoidance. The blue box represents the collision avoidance module, and the red box represents the decision-making module. The input of the overall procedure is composed of three datasets: (1) traffic ship data provided by navigational aid systems such as the automatic radar plotting aid (ARPA), and the automatic identification system (AIS), (2) own ship data obtained from the global positioning system (GPS), inertial navigation system (INS), etc., and (3) waypoint data representing the global path to be followed. The collision avoidance is not conducted in the absence of traffic ships, whereas waypoint tracking is always executed regardless of the existence of traffic ships.

The collision avoidance module consists of five sub-procedures: encounter situation analysis, encounter-type classification, intent inference, probability mapping, and collision avoidance path planning. When a traffic ship is detected, the algorithm determines whether or not it will be in an encounter situation. Once the traffic ship is recognized as an encountered ship, the encounter type is classified according to the COLREGs, and then the maneuver intention of the traffic ship is estimated by the intent inference algorithm. It is not straightforward to convert the probability of the maneuver intention of the traffic ship directly into an evasive action. Therefore, the estimated probability is mapped onto the action space through parameterization suggested in Section II-E, and the collision avoidance path planning is designed based on the result of R-fPVO.

Then, the decision-making module determines the final maneuver decision: approaching the next waypoint, stand-on, or give-way. This final decision is represented in the form of velocity commands for approaching the next waypoint $\mathbf{v}_{\mathrm{wp}}$, velocity for the stand-on (own ship) $\mathbf{v}_{\mathrm{O}}$, and velocity for the give-way $\mathbf{v}_{\mathrm{ca}}$, respectively. The existing decision-making scheme for conflict resolution is extended to consider the rule-violating ship during a multi-ship encounter.

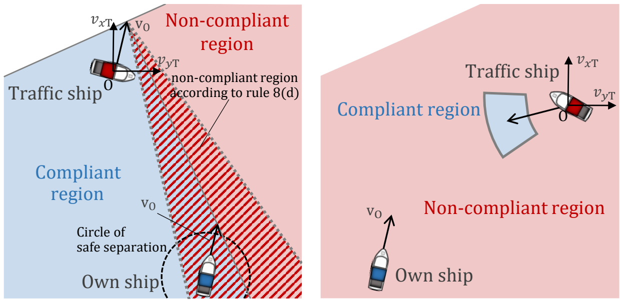
A. Modeling backgrounds

The subscripts O and T indicate the variables for the own ship and the traffic ship, respectively. $\mathbf{x}$ is the state in the north-east-down (NED) coordinates, and it includes the positions $[x, y]^\top$, speed V, and heading ψ. The velocity in the NED coordinates is expressed as $\mathbf{v} = [v_x, v_y]^\top$. The control input is expressed as $\mathbf{u} = [a, \omega]^\top$, where a and ω represent the linear acceleration and turn rate, respectively. The maneuver intention I, which is associated with either rule-compliance or rule-violation, is assumed to be mutually exclusive in the sense that the operator cannot have the intention to comply with the rule and the intention to violate the rule simultaneously.

The own ship is under control and can measure its states using GPS and INS. Additionally, it can observe the state of other ships (i.e., traffic ships) using navigational aid devices such as marine radar. However, the intention of the traffic ship is not directly available to the own ship unless broadcasted through communication channels, and thus it has to be inferred from the given information and observations.

B. Encounter situation analysis

Here, the algorithm determines whether the own ship will be in an encounter situation with the traffic ship. For this, the distance to the closest point of approach (DCPA), time to



(a) Give-way for traffic ship (b) Stand-on for traffic ship

Fig. 3. Regions of compliant and non-compliant velocities considering COLREG rules 8(d) and 13 to 17: the blue ship is the own ship, and the red ship is the traffic ship.

the closest point of approach (TCPA), and distance between two ships are considered. The encounter with the j^{th} traffic ship is indicated by a Boolean variable, which is defined as follows:

$$bEncounter_j = \begin{cases} true, & \text{if } ((0 < TCPA_j < \gamma_{TCPA}) \wedge (DCPA_j < \gamma_{DCPA})) \\ & \qquad \vee (Dist_j < \gamma_{Dist}) \\ false, & \text{otherwise}, \end{cases} \tag{1}$$

where γ_{TCPA}, γ_{DCPA}, and γ_{Dist} represent the threshold values of the TCPA, DCPA, and instantaneous distance, respectively. $TCPA_j$, $DCPA_j$, and $Dist_j$ represent the TCPA, DCPA, and instantaneous distance associated with the j^{th} traffic ship. If the j^{th} traffic ship is determined to be an encounter ship, $bEncounter_j$ is $true$; otherwise, $bEncounter_j$ is $false$.

C. Encounter-type classification

The COLREGs provide guidelines for the encounter-type classification based on the geometry between two ships in rules 13-15: overtaking, head-on, and crossing. However, they only define the basic role classification for conflict resolution in ideal encounter situations. Because of the inherent ambiguity in the interpretation of the rules, a real-world encounter situation can be differently understood by each ship. To resolve these potential inconsistencies, both relative bearing and relative course are used for a precise role classification. Additionally, the rule is extended to the role $\mathcal{R}$, which consists of the overtaking, overtaken, starboard crossing, port crossing, and head-on, and its corresponding action to be taken at each encounter is defined as either give-way or stand-on [10].

D. Intent inference

The intent inference algorithm estimates the intention of traffic ships on rule compliance using the time history of other vessels' state information. To infer the intention, graphical models considering the time history of states are used [24]. The graphical model is designed based on the dynamic Bayesian network that represents the evolution of the state, measurement, and action [26]. To consider the intention, the basic network is updated with the graphical model that describes how the intention affects the other variables. The resulting graphical model is used to derive the recursive form of the equation from the belief of intention and the resulting belief function given states can be expressed as follows:

$$\begin{aligned} p(I_k|\mathbf{x}_{0:k}) = &\eta_k \int_{\mathbf{u}_k} p(\mathbf{x}_k|\mathbf{u}_k, \mathbf{x}_{k-1}) p(\mathbf{u}_k|I_k, \mathbf{x}_{k-1}) \\ &\sum_{I_{k-1}} p(I_k|I_{k-1}) p(I_{k-1}|\mathbf{x}_{0:k-1}) d\mathbf{u}_k, \end{aligned} \tag{2}$$

where $\eta_k = 1/p(\mathbf{x}_k|\mathbf{x}_{0:k-1})$ is the normalizer, and the subscript k is the timestep. The subscript $k_1 : k_2$ represents the time history from k_1 to k_2. Since the intent inference aims to predict the intention of the traffic ship, in Eq. (2), I_k represents the intention of the traffic ship at timestep k. In addition, $\mathbf{x}_k$ and $\mathbf{u}_k$ represent the states and actions of the corresponding ship at timestep k, respectively.

The state transition probability $p(\mathbf{x}_k|\mathbf{u}_k, \mathbf{x}_{k-1})$ is parameterized using a Gaussian distribution as follows:

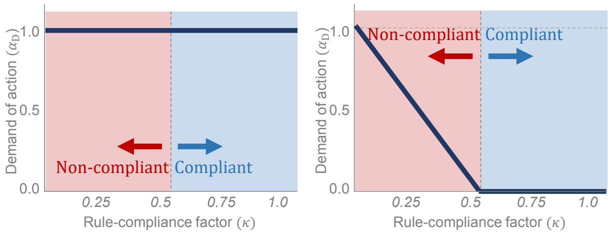
$$p(\mathbf{x}_k|\mathbf{u}_k, \mathbf{x}_{k-1}) \sim \mathcal{N}\left(\mathbf{x}_k; f(\mathbf{x}_{k-1}, \mathbf{u}_k), Q_k\right), \tag{3}$$

where Q_k is the covariance of the process noise and $f(\mathbf{x}_{k-1}, \mathbf{u}_k)$ is the process model using state propagation with actions. The intent transition probability $p(I_k|I_{k-1})$ is also parametrized using a transition matrix. The intention-reflected action probability $p(\mathbf{u}_k|I_k, \mathbf{x}_{k-1})$, which is the probability distribution of control input for the traffic ship given the previous state and intention, is modeled using particle approximation [27]. The model of intention-reflected action probability varies with respect to the action to be taken for the traffic ship because compliance or violation is judged according to the action to be taken at each encounter.

The obligations of the give-way and stand-on vessels are specified in COLREG rules 13 to 17, and the give-way ship further complies with rule 8(d) which is written as follows [1]:

- Action to avoid collision (Rule 8(d)): Action taken to avoid collision with another vessel shall be such as to result in passing at a safe distance. The effectiveness of the action shall be carefully checked until the other vessel is finally past and clear.

Figure 3 shows the region of compliant and non-compliant velocities for the traffic ship in the velocity coordinate system. The red region in the figure represents the non-compliant velocity, while the blue region represents the complaint region according to rules 13 to 17. In addition, the red-shaded region in Fig. 3(a) represents the velocity region violating rule 8(d). If the traffic ship operates at the velocity in this red-shaded region, the distance between the two ships can get closer than the predefined safe separation distance, D_{ss}. When the traffic ship is in a give-way situation, the own ship considers the traffic ship's intention as rule-compliance only if the traffic ship complies with both rules 16 and 8(d).



(a) Give-way (b) Stand-on

Fig. 4. Mapping functions from the rule-compliance factor to the DEA: (a) if the own ship is a give-way vessel, and (b) if the own ship is a stand-on vessel.

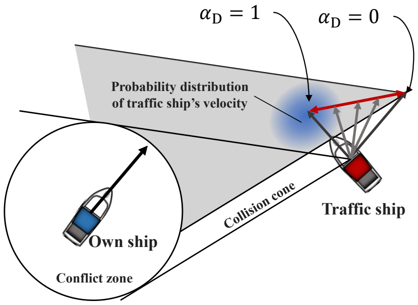


Fig. 5. Graphical representation of the R-fPVO: the red line is the endpoint of the traffic ship's velocity according to the DEA.

For the traffic ship to avoid the own ship passing port-to-port assuring safe separation, its velocity should be in the compliant region with no overlap with the red-shaded region. The obtained regions, which represent the target states to achieve the intention, are mapped into the action using the state propagation model, and then the distribution of the action is used to model the intention-reflected action probability [24].

E. Probability mapping

It is not straightforward to apply the probability of the intention of rule compliance to collision avoidance. Therefore, the procedure of probability mapping is introduced, which maps the probability of rule compliance for the j^{th} traffic ship, $p_{c,j}$, into a parameter which reflects the demand for collision avoidance. For this, the probability of compliant intention is first converted into the rule-compliance factor, κ_j, using an integrator-based filter in order to avoid undesirable chattering and strengthen the belief about the intention. The rule-compliance factor is calculated as follows:

$$\kappa_{j,k} = \kappa_{j,k-1} + \gamma_I (p_{c,j,k} - 0.5), \tag{4}$$

where γ_I represents the gain of the integrator, and the rule-compliance factor is bounded between 0 and 1.

Then, the rule-compliance factor is mapped into the demand of evasive action (DEA) associated with the j^{th} traffic ship, $\alpha_{\mathrm{D},j}$. The DEA represents the degree of necessity of taking an evasive action by the own ship for collision avoidance. Figure 4 shows the mapping function from the rule-compliance factor to the DEA for the own ship. For example, when the own ship is in a give-way situation, it always has the responsibility to avoid collision regardless of the rule-compliance factor value. On the other hand, when the own ship is in a stand-on situation, there is no need for an evasive action by the own ship if the opponent traffic ship complies with the rules and performs an evasive maneuver. However, if the traffic ship does not take any action complying with the rules ($\kappa < 0.5$), the own ship is set to perform an evasive action by increasing the DEA to avoid any potential collision.

F. Reciprocal fast probabilistic velocity obstacle

The PVO algorithm is an extension of the VO algorithm that can generate the evasive action against multiple moving obstacles considering uncertainties. However, the original PVO is computationally expensive since it involves a numerical integration over an infinitesimal area element. Therefore, the fPVO is introduced as an efficient calculation method for computing the PVO using the Gauss-Legendre formula and affine transformation [10]. The pairwise fPVO for the j^{th} traffic ship can be calculated as follows:

$$\begin{aligned}&\mathrm{fPVO}_{\mathrm{OT}_j}(\mathbf{v}_i)\\&= \int_{CC(\mathbf{v}_i)} \eta \exp\left(-\frac{1}{2}\left(\mathbf{v}-\mathbf{v}_{\mathrm{T},j}\right)^\top \Sigma_{\mathrm{T},j}^{-1}\left(\mathbf{v}-\mathbf{v}_{\mathrm{T},j}\right)\right)\mathrm{d}\mathbf{v},\end{aligned} \tag{5}$$

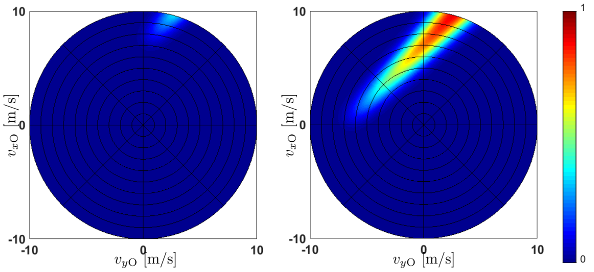
where $CC(\cdot)$ represents the collision cone, $\mathbf{v}_i$ represents accessible velocity of the own ship, and $\eta = \left(2\pi\sqrt{|\Sigma_{\mathrm{T},j}|}\right)^{-1}$. $\mathbf{v}_{\mathrm{T},j}$ and $\Sigma_{\mathrm{T},j}$ represent the mean and covariance of the velocity of the j^{th} traffic ship. The study proposes the use of the R-fPVO method incorporating the concept of coordination in which two ships share the efforts to avoid collision. For this, $\mathbf{v}_{\mathrm{D},j}$, which is coupled with $\alpha_{\mathrm{D},j}$ and $\mathbf{v}_{\mathrm{T},j}$, is newly defined and the resulting R-fPVO can be expressed as follows:

$$\begin{aligned}&\text{R-fPVO}_{\mathrm{OT}_j}(\mathbf{v}_i)\\&= \int_{CC(\mathbf{v}_i)} \eta \exp\left(-\frac{1}{2}\left(\mathbf{v}-\mathbf{v}_{\mathrm{D},j}\right)^\top \Sigma_{\mathrm{T},j}^{-1}\left(\mathbf{v}-\mathbf{v}_{\mathrm{D},j}\right)\right)\mathrm{d}\mathbf{v},\end{aligned} \tag{6}$$

where $\mathbf{v}_{\mathrm{D},j} = \alpha_{\mathrm{D},j}\mathbf{v}_{\mathrm{T},j} + (1-\alpha_{\mathrm{D},j})\mathbf{v}_{\mathrm{O}}$. When multiple ships are encountered, the combined R-fPVO can be calculated as follows:

$$\text{R-fPVO}_{\mathrm{O}}(\mathbf{v}_i) = 1 - \prod_{j=1}\left(1 - \text{R-fPVO}_{\mathrm{OT}_j}(\mathbf{v}_i)\right). \tag{7}$$

Figure 5 shows a graphical representation of R-fPVO. The circular conflict zone with the acceptable separation is defined around the own ship. The endpoint of the traffic ship's velocity changes along the red line depending on the value of DEA. If the own ship has a full DEA ($\alpha_{\mathrm{D}} = 1$), $\mathbf{v}_{\mathrm{D}}$ is equal to $\mathbf{v}_{\mathrm{T}}$, and the result of R-fPVO is identical to that of fPVO. Figure 6 shows the results of R-fPVO according to the DEA in the velocity frame of the own ship. Red represents a high risk, whereas blue represents a low risk. The figure shows that the level of risk grows as α_{D} increases.



(a) $\alpha_\mathrm{D} = 0.0$ (b) $\alpha_\mathrm{D} = 1.0$

Fig. 6. Results of R-fPVO in the velocity coordinates of the own ship. The state of the own ship is $\mathbf{x}_\mathrm{O} = [\,0.0\ 600.0\ \cdot\ \cdot\,]^\top$ and the state of the traffic ship is $\mathbf{x}_\mathrm{T} = [\,600.0\ 0.0\ \text{-}\pi/2.0\ 7.0\,]^\top$.

Algorithm 1 Pairwise encounter situation analysis

```
Input: Role $\mathcal{R}_j$, probability of rule compliance $p_{c,j}$
Output: Action decision boolean variable $\{bExStandon_j, bExGiveway_j\}$
Procedure:
if $\mathcal{R}_j$ is overtaken or port crossing then
    if $p_{c,j} > 0.5$ then
        $bExGiveway_j \leftarrow false$
        $bExStandon_j \leftarrow true$
    else
        $bExGiveway_j \leftarrow true$
        $bExStandon_j \leftarrow false$
    end if
else if $\mathcal{R}_j$ is head-on, overtaking, or starboard crossing then
    $bExGiveway_j \leftarrow true$
    $bExStandon_j \leftarrow false$
end if
```

Algorithm 2 Action selection

```
Input: Action decision boolean variable $\{bEncounter, bExGiveway, bExStandon\}$, velocity for stand-on $\mathbf{v}_\mathrm{O}$, velocity for approaching next waypoint $\mathbf{v}_\mathrm{wp}$, velocity for give-way $\mathbf{v}_\mathrm{ca}$, cost of give-way action $J_\mathrm{a}(\mathbf{v}_\mathrm{ca})$, cost of stand-on action $J_\mathrm{a}(\mathbf{v}_\mathrm{O})$
Output: Final maneuver decision $\mathcal{C}$, desired velocity $\mathbf{v}_\mathrm{d}$
Procedure:
if $bEncounter$ is $false$ then
    $\mathcal{C} \leftarrow$ approaching the next waypoint and $\mathbf{v}_\mathrm{d} \leftarrow \mathbf{v}_\mathrm{wp}$
else if $bExGiveway$ is $false$ then
    $\mathcal{C} \leftarrow$ stand-on and $\mathbf{v}_\mathrm{d} \leftarrow \mathbf{v}_\mathrm{O}$
else
    if $bExStandon$ is $false$ then
        $\mathcal{C} \leftarrow$ give-way and $\mathbf{v}_\mathrm{d} \leftarrow \mathbf{v}_\mathrm{ca}$
    else
        if $J_\mathrm{a}(\mathbf{v}_\mathrm{ca}) > J_\mathrm{a}(\mathbf{v}_\mathrm{O})$ then
            $\mathcal{C} \leftarrow$ stand-on and $\mathbf{v}_\mathrm{d} \leftarrow \mathbf{v}_\mathrm{O}$
        else
            $\mathcal{C} \leftarrow$ give-way and $\mathbf{v}_\mathrm{d} \leftarrow \mathbf{v}_\mathrm{ca}$
        end if
    end if
end if
```

G. Cost function

The velocity for collision avoidance, $\mathbf{v}_\mathrm{ca}$ is computed considering waypoint tracking, COLREG constraints, and R-fPVO. For this, the cost function J is defined as follows:

$$\begin{aligned} J(\mathbf{v}_i) &= J_\mathrm{a}(\mathbf{v}_i) + w_V|V_i - V_\mathrm{wp}| + w_\psi|\psi_i - \psi_\mathrm{wp}|, \\ J_\mathrm{a}(\mathbf{v}_i) &= \text{R-fPVO}_\mathrm{O}(\mathbf{v}_i) + w_f f_\mathrm{COLREG}(\mathbf{v}_i), \end{aligned} \tag{8}$$

where w_V, w_ψ, and w_f are weighting factors. V_wp and ψ_wp are the speed and course for waypoint tracking. f_COLREG is the cost of violating the COLREGs, which is defined as follows:

$$f_\mathrm{COLREG}(\mathbf{v}_i) = \kappa_\mathrm{max}(\mathbf{v}_i)(1 - \text{R-fPVO}_\mathrm{O}(\mathbf{v}_i)), \tag{9}$$

where κ_max is the coefficient of the COLREG cost to consider other vessels' rule violations, and it can be expressed as follows:

$$\kappa_\mathrm{max}(\mathbf{v}_i) = \begin{cases} \max\limits_{j \in \mathcal{I}_i} \kappa_j, & |\mathcal{I}_i| > 0 \\ 0, & \text{otherwise}, \end{cases} \tag{10}$$

where $\mathcal{I}_i$ is the set of indices of the traffic ships to which the own ship will violate the rule when the velocity of the own ship is $\mathbf{v}_i$ [7]. Collisions should be avoided even if the COLREGs are violated in dangerous situations, and thus f_COLREG is inversely proportional to R-fPVO. w_f is limited to 1 to ensure that the COLREG cost does not affect the total cost J more than R-fPVO. The velocity for give-way is the velocity that minimizes the cost, and it can be expressed as follows:

$$\mathbf{v}_\mathrm{ca} = \arg\min_{\mathbf{v}_i} J(\mathbf{v}_i). \tag{11}$$

H. Action selection

Considering the cost function defined earlier, the action selection algorithm makes a maneuver decision, among approaching the next waypoint $\mathbf{v}_\mathrm{wp}$, stand-on $\mathbf{v}_\mathrm{O}$, and give-way $\mathbf{v}_\mathrm{ca}$. To determine the maneuver, first, the encounter situation is analyzed based on situational awareness information provided by navigational aid systems. Algorithm 1 shows how the pairwise encounter situation is described using Boolean variables: $bExGiveway_j$ and $bExStandon_j$. If $bExStandon_j$ is $true$, the own ship maintains its course and speed with respect to the j^{th} traffic ship. However, if $bExGiveway_j$ is $true$, the own ship must avoid the traffic ship either to comply with the rule or to respond to the other ship's rule violation.

The Boolean variables with no subscript, $bExStandon$ and $bExGiveway$ represent the combined Boolean variables which are expressed as follows:

$$\begin{aligned} bEncounter &= \bigvee_{j \in \mathcal{T}} bEncounter_j, \\ bExGiveway &= \bigvee_{j \in \mathcal{E}} bExGiveway_j, \\ bExStandon &= \bigvee_{j \in \mathcal{E}} bExStandon_j. \end{aligned} \tag{12}$$

Here, $\mathcal{T}$ is the set of traffic ships, and $\mathcal{E}$ is the set of encountered ships. Therefore, $|\mathcal{T}|$ is greater than or equal to $|\mathcal{E}|$. Algorithm 2 describes the action selection procedure according to the Boolean variables determined in Eq. (12). If no traffic ship is encountered, the own ship approaches the next waypoint. In the encounter situation, if $bExGiveway$ is $false$ and $bExStandon$ is $true$, the ship is required to maintain its current course and speed to comply with the COLREGs. Conversely, if $bExGiveway$ is $true$ and $bExStandon$ is $false$, the ship is required to avoid other ships using the velocity $\mathbf{v}_{\mathrm{ca}}$. Lastly, if both variables are $true$, the costs of the stand-on and give-way actions are compared, and the action with the lower cost is selected.

III. SIMULATION RESULTS

Two sets of simulations were performed to verify the performance of the proposed algorithm. The mathematical model of a 75-meter ship was used for dynamics simulations, and the details of the simulation setting are described in Table I. The first set of simulations involved one-to-one encounters in which the own ship used the proposed algorithm, while the opponent ship violated the COLREGs. The second set of simulations involved one-hundred multi-ship encounter situations. In every simulation run, five traffic ships appear simultaneously and approach the center point of the simulation field with a random biased target speed and course to make dangerous encounters. In addition, one of the traffic ships was assumed to violate the COLREGs ignoring the surrounding traffic ships, whereas all the other ships used the proposed algorithm.

variables		**value**	**unit**
AIS uncertainty	x-position	$\mathcal{N}(0, 0.5^2 + v_{x\mathrm{T}}^2/12)$	m
	y-position	$\mathcal{N}(0, 0.5^2 + v_{y\mathrm{T}}^2/12)$	m
	x-velocity	$\mathcal{N}(0, 0.1^2)$	m/s
	y-velocity	$\mathcal{N}(0, 0.1^2)$	m/s
Update rate	simulation	10	Hz
	ship control	2	Hz
	intent inference	0.1	Hz
Safe separation distance (D_{ss})		750	m
w_f		0.9	-
γ_I		0.2	-

TABLE I

SIMULATION PARAMETER SETTINGS

A. Ship traffic simulation in one-to-one encounters

In the first set of simulations, the one-to-one encounter scenario with a rule-violating traffic ship was considered in three situations: head-on, starboard crossing, and port crossing. Additionally, the traffic simulations for the same encounter configurations were conducted assuming that the traffic ship complies with the rules, and the results are compared. In the scenario of rule compliance, the traffic ship selected the give-way or stand-on maneuvers in compliance with the rule. However, in the scenario of rule violation, the traffic ship was set to pass starboard-to-starboard in the head-on and starboard crossing situations, and it was set to maintain its course and speed in the port crossing situation.

Figures 7 and 8 show the results of the traffic ship's compliance and violation, respectively. The upper sub-figures (titled as trajectories) show the ship trajectories, and the lower sub-figures show the probability of compliant intention, rule-compliance factor, and the DEA.

The yellow region in the lower sub-figures is the region representing the duration of the encounter. The rule-compliant factor represents the filtered value of the probability of compliant intention and thus it is much less noisy. As shown in Figs. 7(a) and 7(b), the own ship maintains full DEA to avoid ($\alpha_{\mathrm{D}} = 1$), and it safely avoids a traffic ship. Figure 7(c) shows the results for the port crossing scenario. The own ship initially estimates that the traffic ship may violate the rule. However, after observing its evasive maneuver the own ship updates its estimated intention as rule compliance.

In contrast, Figure 8(a) shows the result with the rule-violating vessel in a head-on situation. The own ship estimates the intention of the traffic ship as rule violation and takes an evasive action violating the rule to avoid collision. Similarly, the own ship predicts the violation of the stand-on duty by the traffic ship, as shown in Fig. 8(b), and it passes the traffic ship on the starboard side. Lastly, in Fig. 8(c), the traffic ship maintains its course and speed violating its give-way duty, and thus the own ship initially estimates that the traffic ship may not comply with the rule and alters its course to the starboard side to pass port-to-port. Subsequently, the conflict is naturally resolved and the probability of compliant intention increases, because the updated encounter condition leads to the COLREG-compliant geometry.

B. Ship traffic simulation in multi-ship encounters

Table II summarizes the result of Monte-Carlo simulations in multi-ship encounter situations where the ships encounter other ships 847 times. The conflict and collision are defined to show the qualitative performance using the closest distance between two ships, which can be categorized as follows:

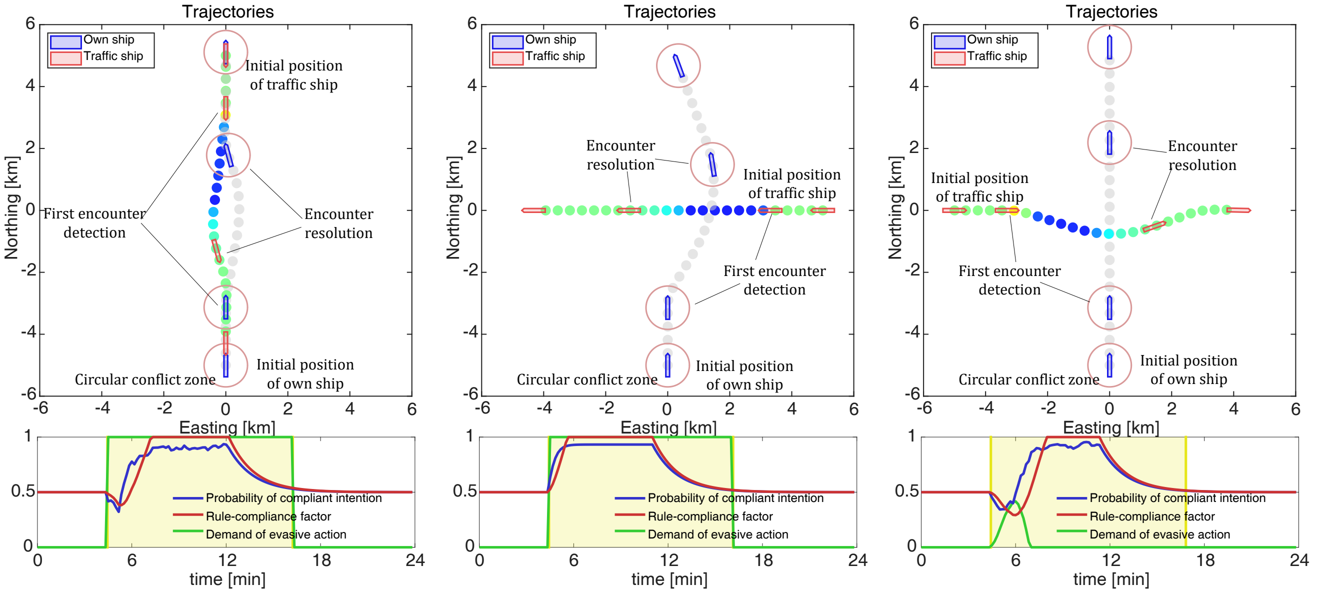
- Conflict: length of ship $\leq \min(Dist_j) < D_{ss}$
- Collision: $\min(Dist_j) <$ length of ship

The result confirms that the proposed approach incorporating the intent inference algorithm can provide reliable and satisfactory collision avoidance performance despite the presence of rule-violating vessels. In the cases of using the standard VO-based collision avoidance methods without the intent inference, many dangerous situations occurred because it is not capable of predicting the rule violation of other ships.

Performance index	**Without intent inference**	**With intent inference (proposed)**
Conflict	54 (6.38%)	15 (1.77%)
Collision	7 (0.83%)	0 (0.0%)

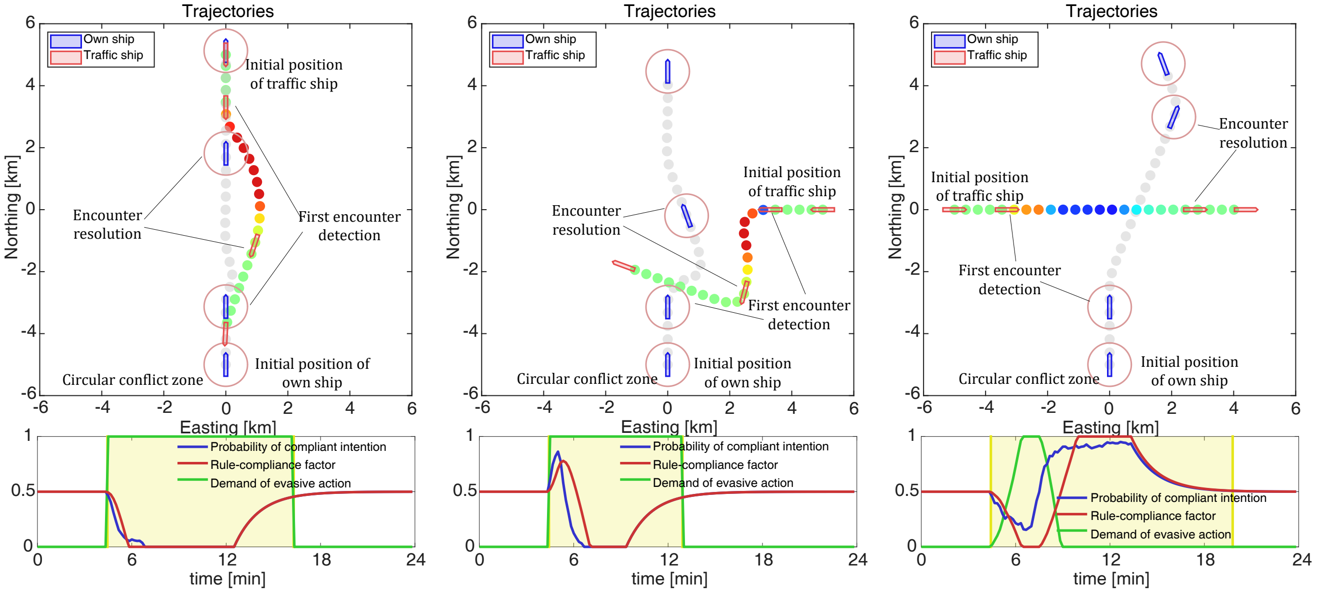
TABLE II

SUMMARY OF 100-CASE MULTI-SHIP ENCOUNTER SITUATIONS



(a) Head-on vessel with the compliant intention (b) Starboard crossing vessel with the compliant intention (c) Port crossing vessel with the compliant intention

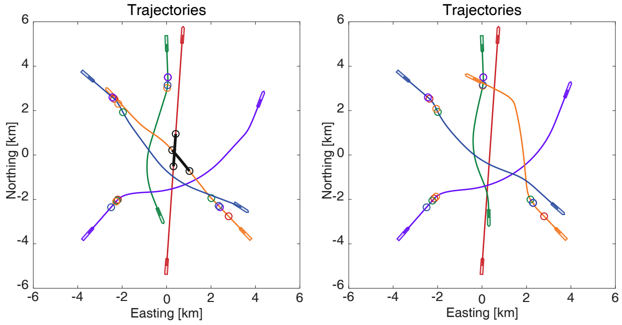
Fig. 7. Simulation results in an encounter situation between two ships: the own ship uses the proposed algorithm and the traffic ship complies with the rule. The circular dots indicate the trajectories of ships (at intervals of 1 min), and the color of the traffic ship indicates the probability of its intention of being compliant to COLREGs. Red, green, and blue represent low values (likely to violate the rules), neutral, and high values (likely to abide by the rules), respectively.



(a) Head-on vessel with the violation intention (b) Starboard crossing vessel with the violation intention (c) Port crossing vessel with the violation intention

Fig. 8. Simulation results in an encounter situation between two ships: the own ship uses the proposed algorithm while the traffic ship violates the rule. The circular dots indicate the trajectories of ships (at intervals of 1 min), and the color of the traffic ship indicates the probability of its intention of being compliant to COLREGs. Red, green, and blue represent low values (likely to violate the rules), neutral, and high values (likely to abide by the rules), respectively.

Figure 9 shows a representative case of Monte-Carlo simulation runs in the multi-ship encounter situations. The left figure shows the result by the VO method without considering the rule violation of other ships, and the right figure shows the result obtained using the proposed algorithm. The colored circle on the trajectory indicates the moment when the corresponding ship was first encountered. The black line indicates the trajectory segment where the distance was shorter than the predefined safe separation distance. In Fig. 9(a), the conflict occurred between the rule-violating ship



(a) Trajectories using VO without intent inference (b) Trajectories using the proposed algorithm

Fig. 9. Simulation results in a multi-ship encounter situation: the red ship is ignorant of other vessels.

and the rule-compliant ship because the rule-compliant ship did not expect the other ship to violate the rule. The results confirm that the proposed algorithm enables predicting the intentions of other vessels and taking appropriate evasive actions and even defensive actions violating the rule if necessary.

IV. CONCLUSION

This study addressed the procedure of the automatic collision avoidance algorithm for situations involving an encounter with COLREG-violating ships. To react to other vessels' rule violations, their intentions were estimated using dynamic Bayesian networks, and the inference results were used to determine the level of DEA for collision avoidance and the degree of rule relaxation. To design the required evasive action the R-fPVO algorithm, which is an extension of fPVO, was newly proposed. We validated the proposed method by performing ship traffic simulations for the one-to-one and multi-ship encounter situations. The simulation results show that the improved safety performance can be achieved by employing the proposed approach in encounter situations involving rule-violating ships.

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