Enabling Vessel Collision-Avoidance Expert Systems to Negotiate

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Abstract

Automatic vessel collision-avoidance systems have been studied in the fields of artificial intelligence and navigation for decades. And to facilitate automatic collision-avoidance decision-making in two-vessel-encounter situation, several expert and fuzzy expert systems have been developed. However, none of them can negotiate with each other as seafarers usually do when they intend to make a more economic overall plan of collision avoidance in the COLREGS-COST-HIGH situations where collision avoidance following the International Regulations for Preventing Collisions at Sea(COLREGS) costs too much. Automatic Identification System(AIS) makes data communication between two vessels possible, and negotiation methods can be used to optimize vessel collision avoidance. In this paper, a negotiation framework is put forward to enable vessels to negotiate to optimize collision avoidance in the COLREGS-COST-HIGH situations at open sea. A vessel vector space is defined and therewith a cost model is put forward to evaluate the cost of collision-avoidance actions. Negotiations between a give-way vessel and a stand-on vessel and between two give-way vessels are considered respectively to reach overall low cost agreements. With the framework proposed in this paper, two vessels involved in a COLREGS-COST-HIGH situation can negotiate with each other to get a more economic overall plan of collision avoidance than that suggested by the traditional collision-avoidance expert systems.

Keywords: Negotiation, vessel collision-avoidance system, AIS

1. Introduction

In recent years, shipping is developing rapidly over the world to meet the growing economic demands. In order to enhance efficiency, improve safety, and overcome the shortage of seafarers, vessels are getting more and more huge and automatic. Collision accidents, however, are increasing as vessels expand in size, in speed and in number [1]. For this reason, the major maritime countries have paid much attention to this problem. Possible solutions are establishing navigation regulations, strengthening traffic controls, improving the technical skills of the seafarers, as well as enhancing the automation level of the vessels. As a major part of vessel automation, automatic vessel collision-avoidance systems have been studied for decades, and are becoming more and more important because of the increasing average loss of collision accidents, of which the main reasons are due to human factors.

In any potential collision situation, the seafarer faces three questions: Does the vessel risk a collision? If yes, should avoiding actions be taken? And what actions should be taken considering all vessels in the vicinity? When a vessel confronts a risk of collision, the seafarer should take actions to avoid the collision. To provide proper advice to avoid collision between two vessels, several collision-avoidance expert systems [2-6] and fuzzy expert systems [1, 7-9] were developed. However, in some COLREGS-COST-HIGH situations, where collision avoidance following the COLREGS[10] costs too much, these systems can not negotiate with each other as seafarers usually do when they intend to make more harmonious and economic overall plan of collision avoidance.

With the appearance of AIS, Automatic Identification System, data communication and automatic negotiation among vessels become possible. This paper proposes a framework to enable vessel collision-avoidance systems to negotiate automatically with each other to get more harmonious and economic overall plan of collision avoidance in two-vessel-encounter situations.

This paper is organized as follows: Section 2 illustrates the related research, including the development of collision-risk-calculation methods between two vessels, the current usage of AIS in collision avoidance and related research in negotiation field. Section 3 presents the concept of vessel vector space and the cost model of a collision-avoidance plan. The former is used to describe the solution space and the latter is the basis of optimization. Section 4 describes the negotiation framework for collision avoidance between a give-way vessel and a stand-on vessel, and the negotiation between two give-way vessels is discussed in section 5. Section 6 presents simulations of the method advanced in this paper. Finally, main conclusion and future researches are offered in section 7.

2. Related Research

The purpose of this research is to use negotiation to eliminate the risk of collision between two vessels, so the utility functions used in the negotiation process are closely related to the risk of collision. Many methods were developed to calculate collision risk between two vessels based on distance and time to the closest point of arrival (DCPA/TCPA), such as weighted method[11], ANN method[12], fuzzy evaluation method [13] and blocking coefficient method[14]. But these methods could not be used to calculate safety utility in the negotiation process as they may lead to multi-times negotiation in one collision-avoidance situation.

It is not a fresh idea to use AIS in collision-avoidance system, but the work before is mainly concentrated on how to use the accurate information of the target vessels provided by AIS in collision-avoidance system [15,16]. Although accurate information of the target vessel is also needed in a negotiation process, AIS looks more like a kind of communication terminals in this research.

Negotiation has been actively studied recently in multi-agent field. This paper borrows some ideas from negotiation field, such as negotiation under time constraints [17], negotiation with incomplete information [18] as well as boulware and conceder models [19].

3. Cost Model

3.1 Vessel Vector Space

When a vessel is in a dangerous encounter situation, it can take actions like changing course, altering speed or both to eliminate the collision risk. If we use a vector with a course and a velocity to describe the navigation state of a vessel, each kind of collision-avoidance action will transfer the vessel from one vector to another since it will change the vessel's velocity, the course or both.

Definition 1. *Continuous Vessel Vector Space. Given a vessel s, its minimum velocity* $v_{\min}$ *and maximum* $v_{\max}$ *, the velocity* $\tilde{V} \in [v^s_{\min}, v^s_{\max}]$ *and the course* $\tilde{C} \in [0, 359]$ *, the cylinder surface formed by* $\tilde{V}$ *as height and* $\tilde{C}$ *as circle is called the continuous vector space of the vessel s, denoted by* $\tilde{\Omega}_s = \tilde{V} \perp \tilde{C}$.

In fact, a vessel's velocity is discrete with the values full astern v_0, half astern v_1, slow astern v_2, dead slow astern v_3, stop v_4, dead slow ahead v_5, slow ahead v_6, half ahead v_7 and full ahead v_8. Course is the same because it is usually changed at least by 1 degree in nautical practice. So the practical vector space of a vessel should be discrete.

Definition 2. *Discrete Vessel Vector Space. Given a vessel s and its bell velocity value set* $V_S = \{v_0, v_1, v_2, v_3, v_4, v_5, v_6, v_7, v_8\}$*, the velocity* $V \in V_S$ *and the integer course* $C \in [0, 359]$*, the cylinder surface like grid space (Figure.1) formed by V as height and C as circle is called the discrete vector space of the vessel s, denoted by* $\Omega_s = V \perp C$.

The cylinder surface like Ω_s can be easily expanded to a flat one in Figure 1. Each sub-space like shadow part in Figure 1 can be defined by definition 3.

Definition 3. *Discrete Vessel Vector Sub-space. Given two coordinates* $X(c_x, v_x)$ *and* $Y(c_y, v_y)$ *in* Ω_s*, the rectangle with* $X(c_x, v_x)$ *as the left-top point and* $Y(c_y, v_y)$ *as the right-bottom point is a discrete vessel vector sub-space of the vessel s, denoted by* $\Omega_s < X, Y >$.

A collision-avoidance plan of *s* can be defined in Ω_s by definition 4.

Definition 4. *Collision-Avoidance Plan. Given a vessel s, its current vector* (c^c_s, v^c_s) *and objective vector* (c^o_s, v^o_s) *, a collision-avoidance plan can be described in* Ω_s *as the edge from point* (c^c_s, v^c_s) *to point* (c^o_s, v^o_s) *(in Figure 1), denoted by* $I^s < (c^c_s, v^c_s), (c^o_s, v^o_s), d_s >$ *,where* d_s *denotes the transition direction on C-axis. It will be true when s plans to turn starboard and will be false otherwise.*

The objective vector of a give-way vessel's collision-avoidance plan may be admitted by COLREGS sometimes and may not be at other times. All admitted objective vectors of a collision-avoidance plan form a COLREGS admitted objective vector space.

Definition 5. *COLREGS Admitted Objective Vector Space. Given a give-way vessel s and its discrete vector space* Ω_s*, the space formed by the objective vectors, which are in* Ω_s *and permitted by the COLREGS, is the current COLREGS Admitted Objective Vector Space of s, denoted by* $\Omega^{\ulcorner}_s$.

The opposite to $\Omega^{\ulcorner}_s$ is the COLREGS Prohibited Vessel Objective Vector Space, denoted by $\Omega^{\lrcorner}_s$, and $\Omega_s = \Omega^{\lrcorner}_s \cup \Omega^{\ulcorner}_s$.

3.2 Cost Model for Collision-Avoidance Plan

If a weight is put on each edge of Ω_s, we will get a weighted discrete vessel vector space (Figure 1), denoted by $\bar{\Omega}_s$. A weight means a cost in this research.

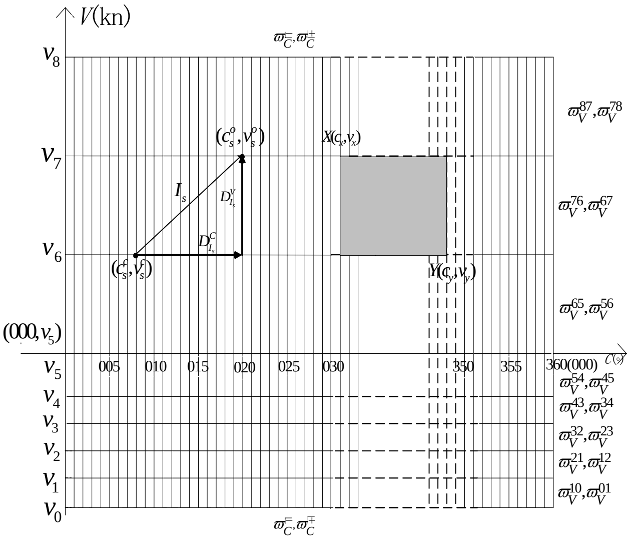

Figure 1. Vessel weighted discrete flat vector space

$\varpi_V^{n(n-1)} (n \in [1,8])$ in Figure 1 means the cost for vessel *s* to alter from n level velocity to n-1 level velocity, while $\varpi_V^{(n-1)n} (n \in [1,8])$ means the contrary. $\varpi_C^{\pm}$ and $\varpi_C^{\mp}$ mean the cost to turn starboard and port by one degree respectively when $V \geq v_5$. $\varpi_C^{\mp}$ and $\varpi_C^{\pm}$ mean the contraries.

Given $\bar{\Omega}_s$ of a vessel *s*, we can calculate the cost of a collision-avoidance plan of *s*, $I^s < (c^c_s, v^c_s), (c^o_s, v^o_s), d_s >$, by equation (1).

$$D_{I^s}(\bar{\Omega}_s) = D^V_{I^s}(\bar{\Omega}_s) + D^C_{I^s}(\bar{\Omega}_s) \qquad (1)$$

Where $D^V_{I_s}$ and $D^C_{I_s}$ are the costs from point (c^c_s, v^c_s) to point (c^o_s, v^o_s) along *V* axis and *C* axis respectively, and both can be calculated by addition. But when one point is above *C* axis and the other one is under *C* axis, we will get two values for $D^C_{I_s}$ due to the difference between $\varpi_C^{\pm}$ and $\varpi_C^{\mp}$, as well as that between $\varpi_C^{\mp}$ and $\varpi_C^{\pm}$. We let the minimum one be the value of $D^C_{I_s}$ in this kind of cases.

Given $\bar{\Omega}_s$ of a vessel *s* and a collision-avoidance plan I^s, we can define a weighted vessel objective vector subspace, denoted by $\bar{\Omega}_s(I^s)$, in which each vector has a cost less than that of I^s.

Given a give-way vessel *b* and a stand-on vessel *p*, their gross tonnage g_b and g_p , their weighted vector space $\bar{\Omega}_b$ and $\bar{\Omega}_p$, *p*'s current velocity v^c_p , and *b*'s collision-avoidance plan $I^b < (c^c_b, v^c_b), (c^o_b, v^o_b), d_b >$, and supposed both *b* and *p* are sailing at normal velocity, *p* can use equation (2) to estimate the cost at which *b* put I^b in practice.

$$D_{I^b}(\bar{\Omega}_p) = D_{I^{p'}}(\bar{\Omega}_p) \times \frac{g_b}{g_p} \qquad (2)$$

Where $I^{p'} = < (c^{c'}_p, v^{c'}_p), (c^{o'}_p, v^{o'}_p), d'_p >$, $c^{c'}_p = c^c_b$, $v^{c'}_p = v^c_p$, $c^{o'}_p = c^o_b$, $d'_p = d_b$, and $v^{o'}_p$ is equal to the velocity value in Ω_p which is closest to $v^c_p v^o_b / v^c_b$.

4. Negotiation Framework In Unequal Encounter Situations

4.1 Preference Model

In an unequal two-vessel-encounter situation, one vessel can be either a give-way vessel or a stand-on vessel. Different role means different preference model. The preference model of a give-way vessel includes four sub-models. (1) the negotiation-intention model ; (2) the negotiation-strategy model; (3) the collision-risk-tolerance model; and (4) the collision-avoidance-action-preference model. The preference model of a stand-on vessel also includes an action-preference model and a risk tolerance model as described above. A benevolence model is also included in addition.

4.1.1 The negotiation-intention model of a give-way vessel

A negotiation-intention model of a give-way vessel *b*, denoted by P_I^b, describes the favor degree of using negotiation when a give-way vessel encounters a collision risk and $P_I^b = < B, M, \varphi_b, \kappa_b >$, where $B = < \Delta_c^-, \Delta_c^+, \Delta_v^- >$, $M = < \Theta_c^+, \Theta_c^-, \Theta_v^+, \Theta_v^- >$ and φ_b is used to define a negotiation-intention curve to the stand-on vessels with different gross tonnages. A bigger φ_b makes *b* more like to negotiate with a smaller stand-on vessel and less to negotiate with a larger one. Given φ_b, the gross tonnages of *b* and a stand-on vessel *p*, denoted by g_b and g_p respectively, *B* describes a vessel vector sub-space $\Omega_{bB} < (c_b^c \oplus \Delta_c^-(\frac{g_p}{g_b})^{\varphi_b}, v_b^c), (c_b^c \oplus \Delta_c^+(\frac{g_p}{g_b})^{\varphi_b}, v_b^c + \Delta_v^-(\frac{g_p}{g_b})^{\varphi_b}) >$ and its cost equivalent $\bar{\Omega}_{bB} < (c_b^c \oplus \Delta_c^-(\frac{g_p}{g_b})^{\varphi_b}, v_b^c), (c_b^c \oplus \Delta_c^+(\frac{g_p}{g_b})^{\varphi_b}, v_b^c + \Delta_v^-(\frac{g_p}{g_b})^{\varphi_b}) >$, where c_b^c and v_b^c are the current course and velocity of *b* respectively, and $\oplus$ is a course plus operator that can be defined in equation (3).

$$C \oplus \Delta_C = \begin{cases} C + \Delta_C & if \quad 000 \le C + \Delta_C < 360 \\ C + \Delta_C + 360 & if \quad C + \Delta_C < 000 \\ C + \Delta_C - 360 & if \quad C + \Delta_C \ge 360 \end{cases} \qquad (3)$$

If the objective vector of a safe and most economic collision-avoidance plan generated by *b* alone, denoted by I_b^*, does not belong to Ω_B, will decide to negotiate with the stand-on vessel for collision avoidance.

M also describes a vessel vector sub-space $\Omega_{bM} < (c_b^c \oplus \Theta_c^-(\frac{g_p}{g_b})^{\varphi_b}, v_b^c + \Theta_v^+(\frac{g_p}{g_b})^{\varphi_b}), (c_b^c \oplus \Theta_c^+(\frac{g_p}{g_b})^{\varphi_b}, v_b^c + \Theta_v^-(\frac{g_p}{g_b})^{\varphi_b}) >$ and its cost equivalent $\bar{\Omega}_{bM} < (c_b^c \oplus \Theta_c^-(\frac{g_p}{g_b})^{\varphi_b}, v_b^c + \Theta_v^+(\frac{g_p}{g_b})^{\varphi_b}), (c_b^c \oplus \Theta_c^+(\frac{g_p}{g_b})^{\varphi_b}, v_b^c + \Theta_v^-(\frac{g_p}{g_b})^{\varphi_b}) >$. If I_b^* does not belong to Ω_{bM}, will negotiate with the stand-on vessel whether it can take any collision-avoidance action together with *b*. In general, $\Omega_{bB} \subseteq \Omega_{bM}^{\ulcorner}$.

Finally, κ_b is used to determine whether to persuade the stand-on opponent to permit *b* to break the COLREGS. *b* will do so if the ratio between the costs of I_b^* and I_t^b is greater than κ_b, and will not otherwise, where I_t^b is a COLREGS prohibited collision-avoidance plan proposed by *b* when *b* tries to eliminate the collision risk alone at time *t*.

4.1.2 The negotiation-strategy model of a give-way vessel

The negotiation-strategy model of a give-way vessel *b*, denoted by P_S^b, is used to model the negotiation strategy that *b* will adopt in a negotiation progress, and $P_S^b = < \lambda_r, t_{\max}^b, \beta >$, where λ_r denotes the percentage of the collision risk *b* intends to eliminate in its initial proposal of collision-avoidance plan when the stand-on vessel likes to make a collaborative action; $t_{\max}^b$ stands for the maximal time *b* likes to spend on the negotiation; and β represents a coefficient which can be used by *b* to adjust the degree of boulware or conceder [19] in the negotiation process.

Given $\lambda_r, t_{\max}^b$, and β, the percentage of the collision risk which *b* should eliminate in its proposal at time $t \in [0, t_{\max}^b]$ could be calculated by its boulware or conceder function $\phi(t)$. $\phi(t)$ is defined in equation (4).

$$\phi(t) = \lambda_r + (1 - \lambda_r)(\frac{t}{t_{\max}^b})^{\frac{1}{\beta}} \qquad (4)$$

When β equals to 1, $\phi(t)$ will grow up linearly. A bigger β leads to a bigger $\phi(t)$ value at the early stage of the negotiation process. That is to say, the bigger β is, the more conceder *b* is and more quickly negotiation may end. On the contrary, a smaller β leads to more economic negotiation results for *b* while consuming more time. Figure 2 shows the outcome of $\phi(t)$ with different β values.

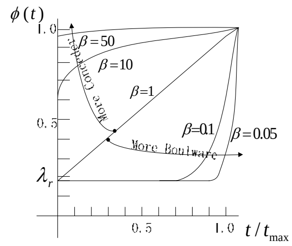

Figure 2. Outcome of boulware and conceder functions

4.1.3 The collision-risk-tolerance model of a give-way vessel or a stand-on vessel

Collision-risk-tolerance model of a vessel *s* ($\in \{b, p\}$), denoted by P_R^s, describes the threshold on distance and time of the target vessel that *s* can tolerate. $P_R^s = < d_s, t_s >$, where d_s denotes the minimum safe passing distance in nautical miles and can be used as the radius to define a safety domain of the vessel; t_s represents the minimum time that *s* can tolerate for the target vessel to enter its domain.

4.1.4 The collision-avoidance-action preference model of a give-way vessel or a stand-on vessel

Collision-avoidance-action-preference model of a vessel $s(\in \{b, p\})$, denoted by P_A^s, is used to describe the preference of *s* to different kinds of collision-avoidance action, and $P_A^s = < p_C^+, p_C^-, P_V^+, P_V^- >$, where p_C^+, p_C^-, P_V^+ and P_V^- describe the preferences of turning to starboard, turning to port, speedup and slowdown respectively with a value limited to the range between zero and one.

Generally, changing course is the preferable action when *s* takes an action in an encounter situation, so both p_C^- and p_C^+ can be set to one. Due to the fact that the values of P_V^+ and P_V^- are closely relevant to the current velocity of *s*, we let v_m ($m \in [5, 8]$) denote the current velocity of *s*, and let $P_V^- = \{p_V^{m(m-i)} \mid 1 \le i \le m\}$ and $P_V^+ = \{p_V^{m(m+i)} \mid 1 \le i \le 8 - m\}$, where $p_V^{m(m-i)}$ denotes the preference of *s* to make a slowdown from *m* level to *m-i* level, and $p_V^{m(m+i)}$ represents the preference of *s* to make a speedup from *m* level to *m+i* level. If *s* prefers to make a slowdown or speedup by one level only when it has to turn to starboard or to port by more than *k* degrees to avoid a collision, then $p_V^{m(m-1)}$ and $p_V^{m(m+1)}(if \quad m < 8)$ could be set to $1/k$. $p_V^{m(m-i)}(1 \le i < m)$ and $p_V^{m(m+i)}(1 < i \le 8 - m)$ could be determined in a similar way.

Given P_A^s, all weights of $\bar{\Omega}_s$ except that of $\varpi_C^{\boxplus}$ and $\varpi_C^{\ulcorner}$, can be determined by equation (5).

It is very difficult to alter courses without an outside force when a vessel is sailing on a negative or zero velocity, so both $\varpi_C^{\boxplus}$ and $\varpi_C^{\ulcorner}$ can be set to $+\infty$.

4.1.5 The benevolence model of a stand-on vessel

According to the COLREGS, a stand-on vessel has no obligation to take any action at the beginning of a developing collision. Most of them, however, are “benevolent” to take a collaboration action when they consider that it will cost the give-way vessel too much to avoid the collision in accordance with the COLREGS. We model this kind of “benevolence” of a

$$\varpi_V^{n(n-1)} = \begin{cases} \frac{1}{p_V^{m(n-1)}} - \frac{1}{p_V^{mn}} & (n \in [1, m-1]) \\ \frac{1}{p_V^{m(m-1)}} & (n = m) \\ +\infty & (n \in [m+1, 8]) \end{cases}$$

$$\varpi_V^{n(n+1)} = \begin{cases} +\infty & (n \in [0, m-1]) \\ \frac{1}{p_V^{m(m+1)}} & (n = m) \\ \frac{1}{p_V^{m(n+1)}} - \frac{1}{p_V^{mn}} & (n \in [m+1, 7]) \end{cases} \quad (5)$$

$$\varpi_C^{\lfloor +} = \frac{1}{p_C^+} \qquad \varpi_C^{\lfloor -} = \frac{1}{p_C^-}$$

stand-on vessel p by P_B^p and $P_B^p = < a_n, a_b, B_\theta, B_\lambda, \varphi_p, t_{\max}^p >$, where a_n is used to determine whether a give-way vessel b, has the qualifications to negotiate with p to avoid collision. b will have while $(g_b / g_p) \geq a_n$ and will not otherwise. a_b is used to decide whether p agrees with the give-way vessel to break the COLREGS. p will agree if $D_{I_b^*}(\bar{\Omega}_p) / D_{I_t^b}(\bar{\Omega}_p) > a_b$, and will not otherwise, where I_t^b is a COLREGS prohibited collision-avoidance plan proposed by b when b tries to eliminate the collision risk alone at time t. B_θ denotes the collaboration threshold vector to the give-way vessel with a gross tonnage equal to that of p and $B_\theta = < \theta_C, \theta_V >$, where θ_C and θ_V stand for the thresholds of the course and the velocity respectively. When the course or the velocity alteration of the give-way vessel with a gross tonnage equal to that of p exceeds θ_C or θ_V, p will like to take some collaborative action. B_λ represents the coefficients by which p will collaborate the give-way vessel with a similar gross tonnage on both course and velocity, and $B_\lambda = < \lambda_C, \lambda_V >$, where λ_C and λ_V denote the collaboration coefficients on course and velocity respectively. φ_p is used to determine the benevolence degree for the give-way vessels with different gross tonnage.

Given a give-way vessel b and its gross tonnage g_b, the collaboration thresholds of the course and the velocity for b, denoted by θ'_C and θ'_V respectively, can be calculated by equation (6).

$$\begin{aligned} \theta'_C &= \theta_C / (\frac{g_b}{g_p})^{\varphi_p} \\ \theta'_V &= \theta_V / (\frac{g_b}{g_p})^{\varphi_p} \end{aligned} \quad (6)$$

And also the collaboration coefficients on the course and the velocity to b, denoted by λ'_C and λ'_V respectively, can be calculated by equation (7).

$$\begin{aligned} \lambda'_C &= \lambda_C \times (\frac{g_b}{g_p})^{\varphi_p} \\ \lambda'_V &= \lambda_V \times (\frac{g_b}{g_p})^{\varphi_p} \end{aligned} \quad (7)$$

$t_{\max}^p$ in P_B^p denotes the maximum time p likes to spend on the negotiation. The bigger $t_{\max}^p$ is, the more benevolent p is.

The preference of a stand-on vessel p can be modeled by $P^p < P_B^p, P_A^p, P_R^p >$ while the negotiation preference of a give-way vessel b, can be modeled by $P^b < P_I^b, P_A^b, P_R^b, P_S^b >$.

4.2 Initiator and Responder

Given an unequal two-vessel encounter situation, a give-way vessel , a stand-on vessel p, their gross tonnage g_b and g_p , b's negotiation-intention model $P_I^b = < B, M, \varphi_b >$ and strategy model $P_S^b = < \lambda_r, t_{\max}^b, \beta >$, p's negotiation-benevolence model $P_B^p = < a_n, a_b, B_\theta, B_\lambda, \varphi_p, t_{\max}^p >$. b will initiate a negotiation process when it is going to encounter the risk of collision with p in $t_{\max}^b$ and $I_b^* \not\subset \Omega_B$ which is determined by B. p will participate in the negotiation progress as the responder when $(g_b / g_p) \geq a_n$.

4.3 Negotiation Issues

Negotiation issues are what give-way vessel b and stand-on vessel p negotiate on. The purpose of the negotiation in this research is to get an overall plan of collision avoidance, including one collision avoidance plan of b and p respectively, to eliminate the collision risk between them and obstacles around. So the negotiation issues, denoted by I, should be the set of the collision-avoidance plan of both vessels', namely, $I = < I^b, I^p >$, where $I^b = < (C_b^c, V_b^c), (C_b^o, V_b^o), d_b >$ and $I^p = < (C_p^c, V_p^c), (C_p^o, V_p^o), d_p >$. b can only alter part of the overall plan in the negotiation process and so does p.

4.4 Utility Function

Given a negotiation process with and , their collision-risk-tolerance-models, $P_R^b < d_s^b, t_s^b >$ and $P_R^p < d_s^p, t_s^p >$, an overall plan of collision avoidance $I_t < I_t^b, I_t^p >$ generated at time $t (0 \leq t \leq t_{max}^b)$. Suposed $I_t < I_t^b, I_t^p >$ is put in practice by b and p after negotiation, the remaining collision risk between b and p can be calculated by equation (8).

$$\begin{aligned} r_x^{I_t} = &(\max\{0, (1 - DCPA^{I_t} / \max\{d_s^b, d_s^p\})\} \\ &+ \max\{0, 1 - TED_{p \to b}^{I_t} / t_s^b, 1 - TED_{b \to p}^{I_t} / t_s^p\}) / 2 \end{aligned} \qquad x \in \{b, p\} \quad (8)$$

Where $DCPA^{I_t}$ is the remaining $DCPA$ if b and p bring I_t into effect, and $TED_{x \to y}^{I_t} (x \in \{b, p\}, y \in \{b, p\}, x \neq y)$ is x's Time to Enter y's Domain (TED) after b and p bring I_t into effect.

Given $r_x^{I_t}$, safety utility of I_t of b and p, denoted by $u_{b_S}^{I_t}$ and $u_{p_S}^{I_t}$ respectively, can be calculated by equation (9).

$$u_{x_S}^{I_t} = 1 - r_x^{I_t}, x \in \{b, p\} \quad (9)$$

Given $\bar{\Omega}_b$ and $\bar{\Omega}_p$, the cost utility of $I_t < I_t^b, I_t^p >$ of b can be calculated by equation (10).

$$u_{b_C}^{I_t} = \begin{cases} 1 & if \quad D_{I_t^b}(\bar{\Omega}_b) < D_{I_b^*}(\bar{\Omega}_b) \\ 0 & otherwize \end{cases} \quad (10)$$

And the cost utility of $I_t < I_t^b, I_t^p >$ of p can be calculated by equation (11).

$$U_{p_C}^{I_t} = \begin{cases} 1 & if \quad (D_{I_t^b}(\bar{\Omega}_p) + D_{I_t^p}(\bar{\Omega}_p)) \leq D_{I_b^*}(\bar{\Omega}_p) \\ 0 & otherwize \end{cases} \quad (11)$$

Equation (11) could guarantee the overall collision-avoidance plan generated by a successful negotiation to cost no more than the plan produced by the collision-avoidance system of b alone.

Given the safe utility function and the cost utility function, the utilities of $I_t < I_t^b, I_t^p >$ of b or p can be calculated by Equation (12).

$$U_x^{I_t} = U_{x_S}^{I_t} \times U_{x_C}^{I_t} \qquad x \in [b, p] \quad (12)$$

4.5 Negotiation Protocol

A give-way vessel b and a stand-on vessel p negotiate with each other according to the following negotiation protocol (see Figure 3):

1) In pre-negotiation stage, b and p will exchange initial

information for the negotiation, i.e. gross tonnages, negotiation time and collision-risk-tolerance models of the two vessels. Then *b* will search out a safe and most economic individual collision-avoidance plan, namely, I_b^*, from $\bar{\Omega}_b^{\Gamma}$. This plan is looked as the one generated by the legacy collision-avoidance system in this paper. Then *b* will decide whether it needs to negotiate with *p*. If it does, *b* will send I_b^* to *p*, and if $t_{max}^b > t_{max}^p$ at the same time, *b* will let $t_{max}^b = t_{max}^p$. *p* will also evaluate whether it is worthy to negotiate with *b* in this stage.

2) A negotiation always starts from *b* with an offer, i.e. a *propose* or a *request*. A *propose* will offer only one proposal while a *request* may offer more. Moreover, in *request* offers the special constant '*?*' must appear. This is regarded as a petition to *p* to make a detailed proposal by filling the '*?*'s with defined values.

3) This is followed by an exchange of possible counter *propose*s, *request*s and *reject*s.

4) Finally, a closing offer is uttered, i.e. an *accept* or a *withdraw*.

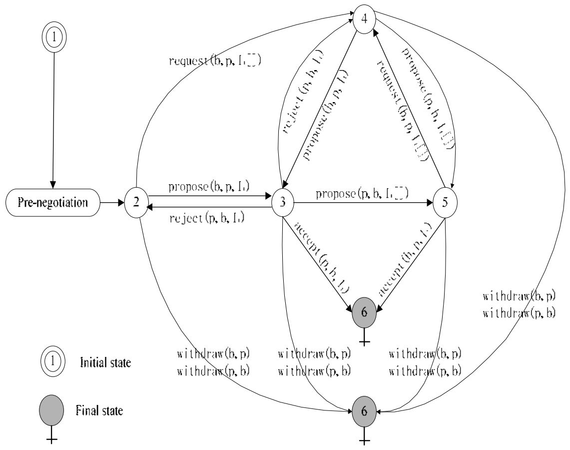

Figure 3. Negotiation protocol

4.6 Reasoning Mechanism

For a give-way vessel *b*, the reasoning mechanism is used to generate the initial offer and the counter offer. For a stand-on vessel *p*, however, it is only used to generate the counter offer.

If *b* tries to inform *p* what its action plan is or to persuade *p* to permit *b*'s breaking of the COLREGS, the negotiation will start from *b* with a *propose* and one safe and most economic proposal which is searched out from $\bar{\Omega}_{bM}^{\perp} \cap \bar{\Omega}_b(I_b^*)$. If *b* tries to persuade *p* to take a collaborative action with *b*, the negotiation will start from *b* with a *request* and a set of scattered and most economic proposals from $\bar{\Omega}_b(I_b^*)$ which could eliminate collision risk by λ_r percents.

When *b* receives a *reject* or a set of proposals from *p*, *b* will accept the proposal or offer a new *request* with a set of scattered and most economic proposals from $\bar{\Omega}_b(I_b^\#)$ which could eliminate collision risk by $\phi(t)$ percents, where $I_b^\#$ is the most economic action plan of *b* generated in the previous negotiation process. When *b* could not get any proposal, *b* will propose $I_b^\#$ to *p*.

When *p* receives a *propose* with a proposal from *b*, *p* will decide whether to accept or to reject the proposal according its benevolence model. When *p* receives a *request* with a set of proposals from *b*, *p* will reply a *propose* with a set of proposals generated with *p*'s benevolence model in an imitative way.

5 Negotiation Between Two Give-way Vessels

In a head-on situation, two vessels involved are give-way vessels to each other according to the CORLEGS. The negotiation between two give-way vessels can also be made under the negotiation framework described in section 4.

In a head-on situation, the vessel that discovers the risk of collision first, which is usually the vessel with greater tonnage due to its larger tolerance model, can act as the negotiation initiator with a more negotiation-favorite and boulware give-way vessel preference model, and the other one can act as the responder with a more charitable benevolence model.

Given a more negotiation-favorite and boulware initiator and a more benevolent responder in a head-on situation, the whole collision-avoidance plan they agree on will be nearly fair to each one.

6 Simulations

Suppose the negotiation rate between the give-way vessel *b* and the stand-on vessel *p* is 10 rounds/min. let *b*'s gross tonnage (g_b) be 15,000T, and its preference model be $P^b < P_I^b, P_S^b, P_A^b, P_R^b >$, where $P_S^b =< 0.3,1,1 >$, $P_R^b =< 2,10 >$ and $P_A^b =< 1,1, <1,1,1,1,1,1,1,1>, <1/90,1/110,1/130, 1/150,1/180,1/180, 1/180,1/180 >>$. Let *p*'s gross tonnage (g_p) be 10,000T, and its preference model be $P^p < P_B^p, P_A^p, P_R^p >$, where $P_A^p =< 1,1,\phi, < 1/90,1/110,1/130, 1/150,1/180,1/180,1/180, 1/180 >>$ and $P_R^p =< 2,8 >$.

In crossing and overtaking situations, let $P_I^b =<< 30,30,0>,<60,60,2,2>,1,2 >$ and $P_B^p = <0.5,2,<10,0>,<0.5,0>,0.5,1>$. In head-on situations, let $P_I^b =<< 0,10,0>,<30,30,2,0>,1,2>$ and $P_B^p = <0.5,2,<0,0>,<1,1>,0.5,1>$.

Table 1 shows the simulation results of five COLREGS-COST-HIGH situations.

Table 1. Simulations of five COLREGS-COST-HIGH situations.

Case	Situation	Result	Save
1	*b*: *x*=2.7 n miles, *y*=2.3 n miles, *C*=0°, *V*=10kn (full ahead) *p*: *x*=7.2 n miles, *y*=4.9 n miles, *C*=270°, *V*=15 kn (full ahead) *DCPA*=0.36 n miles, *TCPA*=17.58 minutes *p*'s time to Enter *b*'s domain = 11 minutes	Expert plan of *b*: <(0°,10kn),(72°,10kn),starboard> Negotiated plan: *b*:<(0°,10kn),(36°,10kn),starboard> *p*:<(270°,15kn),(292°,15kn),starboard>	29.6%
2	*b*: *x*=2.7 n miles, *y*=2.3 n miles, *C*=0°, *V*=10kn (full ahead) *p*: *x*=6.6 n miles, *y*=6.7 n miles, *C*=235°, *V*=15 kn (full ahead) *DCPA*=0.83 n miles, *TCPA*=15.89 minutes *p*'s time to Enter *b*'s domain =11 minutes	Expert plan of *b*: <(0°,10kn),(71°,10kn),starboard> Negotiated plan: *b*:<(0°,10kn),(343°,10kn),port> *p*:<(235°,15kn),(226°,15kn),port>	67.6%

3	*b*: *x*=2.7 n miles, *y*=2.3 n miles, *C*=0°, *V*=15kn (full ahead) *p*: *x*=1.9 n miles, y=5.0 n miles, *C*=0°, *V*=10 kn (full ahead) No. 1 obstacle: *x* =5.1 n miles ,*y*=4.5 n miles No.2 obstacle: *x*=-0.8 n miles, *y* =4.0 n miles *DCPA*=0.76 n miles, *TCPA*=33.22 minutes *p*'s time to Enter *b*'s domain =11 minutes	Expert plan of *b*: <(0°,15kn),(86°,15kn),starboard> Negotiated plan: *b*:<(0°,15kn),(8°,15kn),starboard> *p*:<(0°,10kn),(356°,10kn),port>	88.5%
4	*b*: *x*=2.7 n miles, *y*=2.3 n miles, *C*=0°, *V*=10kn (full ahead) *p*: *x*=2.9 n miles, *y*=8.9 n miles, *C*=180°, *V*=15 kn (full ahead) No. 1 obstacle: *x* =7.06 n miles ,*y*=7.76 n miles *DCPA*=0.20 n miles, *TCPA*=15.78 minutes p's time to Enter b's domain =11 minutes	Expert plan of *b*: <(0°,15kn),(56°,15kn),starboard> Negotiated plan: *b*:<(0°,10kn),(344°,10kn),starboard> *p*:<(180°,15kn),(164°,15kn),port>	52.4%
5	*b*: *x*=2.7 n miles, *y*=2.3 n miles, *C*=0°, *V*=5kn (slow ahead) *p*: *x*=7.2 n miles, *y*=1.5 n miles, *C*=290°, *V*=15 kn (full ahead) *DCPA*=0.70 n miles, *TCPA*=18.96 minutes *p*'s time to Enter *b*'s domain =11 minutes	Expert plan of *b*:<(0°,5kn),(180°,5kn),port> Negotiated plan: *b*:<(0°,5kn),(0°,10kn(full ahead)),null> *p*:<(290°,15kn),(290°,15kn),null>	100%

7 Conclusions And Discussion

This paper proposes a framework to enable vessels to negotiate for collision-avoidance optimization in two-vessel-encounter situations as seafarers do in nautical practice. Negotiation between a give-way vessel and a stand-on vessel and negotiation between two give-way vessels are considered in this paper. Generally, more harmonious and economic collision-avoidance decision can be made with negotiation in the COLREGS-COST-HIGH encounter situations than that made by the legacy collision avoidance expert systems.

This research is a preliminary study on vessel collision avoidance with automatic negotiation, and there are still many open issues related to this research. We have used a real number in the benevolence model of a stand-on vessel to determine whether the stand-on vessel allows a give-way vessel to take an action breaking the CORLEGS, but in nautical practice, the number may vary with different navigating environment around the vessel. The cost model of a collision-avoidance plan is also not perfect now. More factors, such as the location of the next way point and the course change at that point, are to be considered. The stand-on vessel's model to evaluate the cost of a give-way vessel's action plan should be further studied too. How to enable vessels to negotiate for collision avoidance in multi-vessel-encounter situations also needs further research.

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