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A negotiation method for cooperative collision avoidance between ships in mixed navigation scenarios: model construction, strategy driving, and unilateral learning

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ABSTRACT

With the gradual development of Maritime Autonomous Surface Ships (MASS), sea traffic is expected to remain in mixed navigation scenarios where autonomous and conventional ships operate concurrently. General collision avoidance methods and autonomous algorithms resolve encounter situations independently, but disparities in decision-making logic and approaches leave uncoordinated collision risks. This study constructs a bilateral negotiation model that enables autonomous and conventional ships to resolve uncoordinated collision avoidance through negotiation. The Zeuthen strategy is applied to ensure convergence and consensus in bargaining, while unilateral Bayesian learning is embedded to allow autonomous ships to estimate relevant information from conventional ships for improved negotiation capacity. The method exploits the computational capability of autonomous ships while imposing only lightweight information exchange requirements on conventional ships. Simulation experiments in representative mixed navigation scenarios demonstrate that the method resolves previously uncoordinated encounters, eliminates unnecessary evasive maneuvers by autonomous ships, and significantly improves overall navigational safety. This research addresses the limited studies on collaborative collision avoidance in such scenarios, reduces unnecessary active avoidance by autonomous ships, enhances the safety of decision-making for heterogeneous fleets, and provides a reference for the design and optimization of mixed navigation methods.

1. Introduction

The shipping industry is undergoing the challenges of intelligent upgrading due to rapid technological advancements, with the International Maritime Organization (IMO) leading the development of Maritime Autonomous Surface Ships (MASS) [1] to increase automation in maritime transport [2]. However, conventional ships will continue to dominate the market for the foreseeable future, leading to long-term coexistence with autonomous ships in mixed navigation scenarios [3]. This coexistence poses challenges to ship collision avoidance because of differences in autonomy levels, decision-making algorithms, and handling skills. In addition, studies have shown that in mixed navigation environments with multiple ships near coastal

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areas, the uncertainty of target ship motion significantly increases decision complexity [4]. Numerous studies have contributed to autonomous collision avoidance methods, which have proven effective in some scenarios. Research can be broadly classified into two categories. The first includes algorithms based on mathematical models, such as the Velocity Obstacle (VO) method [5], game theory [6], Artificial Potential Field (APF) method [7], and path planning approaches [8]. The second comprises artificial intelligence and computing-based algorithms, including swarm intelligence [9], neural networks [10], biomimetic algorithms [11], reinforcement learning [12], and deep learning [13]. These approaches are proactive collision avoidance strategies from the perspective of the autonomous ship as Own Ship (OS), but they rarely include cooperation or collaboration [14] and remain largely self-contained [15].

Therefore, on the one hand, developing practical algorithms for autonomous ships remains challenging [16]. It is necessary to enhance their collision avoidance capabilities; on the other hand, general collision avoidance methods are unsuitable in mixed navigation because of differing decision-making logic [17]. Collaborative approaches are required to resolve collision avoidance problems in such environments.

Collaborative collision avoidance methods, as an emerging research direction, improve collision avoidance effectiveness in complex maritime scenarios by establishing rules or mechanisms for coordinated decision-making and information sharing among ships. This ensures orderly navigation through synchronized actions, shared navigational data, collision-free maneuver planning, and human-machine interaction. Several successful explorations and applications have been reported. For example, Xu et al. implemented multi-ship collaborative decision control in a wide inland Traffic Separation Scheme (TSS) using a temporal rolling optimization framework, providing a new solution for safe and efficient mixed formations [18]. Veitch and Alsos revealed the active safety role of human operators in autonomous ship systems and highlighted the importance of human–AI collaboration through a systematic review of 42 studies [19]. Porathe proposed a human-automation interaction decision-support framework for autonomous ship remote operation centers [20]. Chen et al. developed a cooperative multi-vessel system for urban waterway networks using an Alternating Direction Method of Multipliers (ADMM)-based negotiation algorithm, achieving unified control of vessel train formation and intersection scheduling [21]. Zaccone and Martelli validated, through simulation, the effectiveness and limitations of Rapidly-exploring Random Tree Star (RRT*)-based COLREGs (International Regulations for Preventing Collisions at Sea)-compliant collision avoidance systems in multi-vessel interaction scenarios [22]. Zaccone further modeled autonomous ship collision avoidance as a multi-stage dynamic programming optimization problem and proposed a greedy approximation algorithm to reduce computational complexity [23]. Rødseth et al. systematically analyzed the information asymmetry problem in mixed traffic between conventional and autonomous ships, proposing short-term human assistance and long-term improvements in information exchange [24].

The methods can be divided into two categories: centralized and distributed. In centralized approaches, a central coordinator exists. For example, Szlapczynski [25] applied evolutionary algorithms and game theory optimization to find the optimal navigation trajectory for all participating ships. Tam and Bucknall [26] proposed a deterministic collaborative path-planning algorithm that provided collision-free paths for all ships by introducing priority evaluation criteria.

In distributed methods, each ship independently makes its collision avoidance decisions and then reaches consensus through communication, negotiation, and interaction, balancing overall collision avoidance benefits. For negotiation methods, Qinyou et al. [27] designed a framework enabling ships to negotiate in "COLREGs-Cost-High" situations to optimize collision avoidance and subsequently improved it [28], achieving more economical solutions when ships deviated from their planned route or approached the next waypoint. Hornauer et al. [29] proposed trajectory optimization based on autonomous negotiation, using a specialized A* algorithm to plan and negotiate trajectories until a solution was reached. After several rounds, feasible and collision-free trajectories were generated. Ma et al. [30] designed a collision avoidance method based on negotiation protocols for unmanned surface vessels, employing Ad hoc networks for inter-ship communication. The self-organizing collaboration model proposed by Wang et al. demonstrated that in restricted one-way waterways, distributed decision-making and yielding mechanisms significantly reduced ship delays and improved efficiency [31].

It can be concluded that negotiation in distributed artificial intelligence is valuable for reaching mutually beneficial agreements [32], particularly in overcoming information asymmetry between unmanned and manned ships [24]. Communication between ships can provide essential information to assist in negotiations and cooperation with target ships (TSs), enabling more effective actions [14]. Despite discussions on collaborative collision avoidance and coordination mechanisms, research on negotiation-based collaboration in mixed scenarios remains limited. This study contributes to the field in three ways. First, it aligns with the current trend of distributed and cooperative decision-making in autonomous navigation, moving beyond single-ship avoidance logic. Second, it addresses the critical gap of information asymmetry and coordination difficulty between autonomous and conventional ships, which has been largely overlooked. Third, it proposes an integrated negotiation framework that enables practical, fair, and adaptive collision avoidance. In doing so, the study not only complements existing autonomous avoidance methods but also promotes a new paradigm for collaborative safety management in mixed navigation scenarios.

2. Methodologies

The initial framework of COLREGs placed limited emphasis on verbal exchanges, focusing instead on visible maneuvers and signaling methods. In navigation involving autonomous vessels, however, a strict prohibition of communication may result in uncertainty and heightened risk. The proposed negotiation strategy enhances COLREGs by introducing machine-readable intent sharing while preserving the fundamental rule-based duties. Existing negotiation models are frequently tailored to specific scenarios, often presuming uniform vessel capabilities, and they generally lack explicit technical procedures.

Negotiation processes for ship collision avoidance should therefore follow straightforward guiding principles. Ideally, in close-range encounters, a vessel should have access to the same information as the Target Ship (TS) to make decisions, rather than having to “guess” the TS’s intentions. The objective is to establish encounter communication, where each ship provides information to the TS to support accurate decision-making in the presence of collision risks [15]. Liu et al. [33] emphasized that communication based on the Automatic Identification System (AIS) is feasible, and emerging technologies such as the VHF Data Exchange System (VDES) and electronic navigation can drive the development of new ship communication systems. It is reasonable to assume that these measures and tools can facilitate cooperation and prevent collisions [15]. With the implementation of the IMO’s e-Navigation concept, new communication technologies are being developed for traditional vessels, enabling ship-to-ship route exchange for conventionally crewed ships. Hence, these tools can reasonably be considered effective in facilitating collaborative collision avoidance.

Autonomous and conventional vessels employ distinct approaches to collision avoidance. Autonomous ships depend on pre-programmed algorithms to make avoidance decisions, whereas conventional navigation relies on the expertise, judgment, and communication of the Officer on Watch (OOW). This contrast demonstrates the computational precision of autonomous ships and the situational adaptability of conventional ships in cooperation and interaction. In view of common vessel encounter situations, the complexity of multi-ship collision avoidance, and the requirement for compliance with COLREGs [34], this study restricts its scope to two-ship encounters as a basis for developing negotiation strategies. Accordingly, collision avoidance negotiation in mixed navigation is considered under the assumption of an encounter between an Autonomous Ship (AS) and a Conventional Ship (CS), within the framework where COLREGs define encounter categories and collision risks.

On this foundation, a novel negotiation method is introduced to enhance collaborative decision-making between vessels, with the overall framework presented in Fig. 1. Both ships are required to evaluate collision risks and identify feasible decisions. When conflicting avoidance measures are detected, negotiation is initiated. The cooperative collision avoidance framework comprises three interdependent elements: (1) an organizational model specifying entities, goals, and utility functions; (2) a procedural model outlining communication rules and protocols; and (3) a unilateral learning mechanism based on Bayesian inference. These elements are sequentially linked: the organizational model establishes the foundation, the procedural model directs the interaction process, the negotiation strategy determines concession patterns, and the learning mechanism enhances adaptability. Detailed explanations of each component are provided in the following subsections.

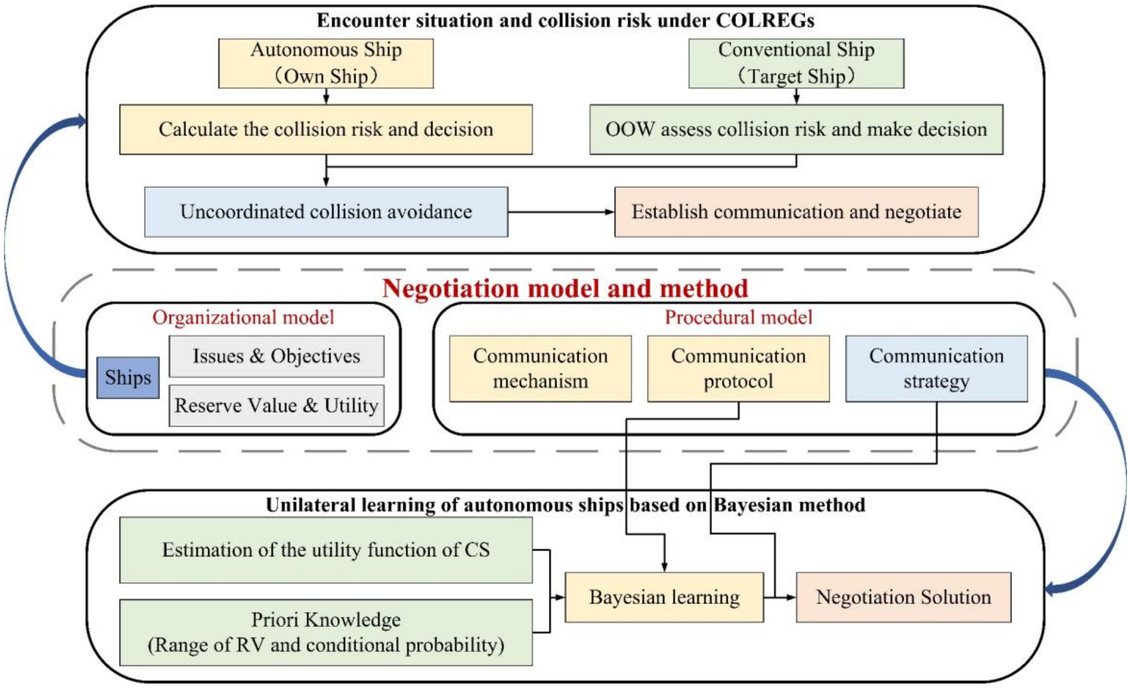


Fig. 1 Overall design of negotiation method

2.1 Organizational model

As the foundation of the framework, the organizational model includes the negotiating entities, issues, objectives, reserve value, and utility value. This structure provides the input basis for subsequent communication protocols and strategy execution. The organizational structure for negotiating collision avoidance decisions between an autonomous vessel and a conventional vessel is shown in Fig. 2.

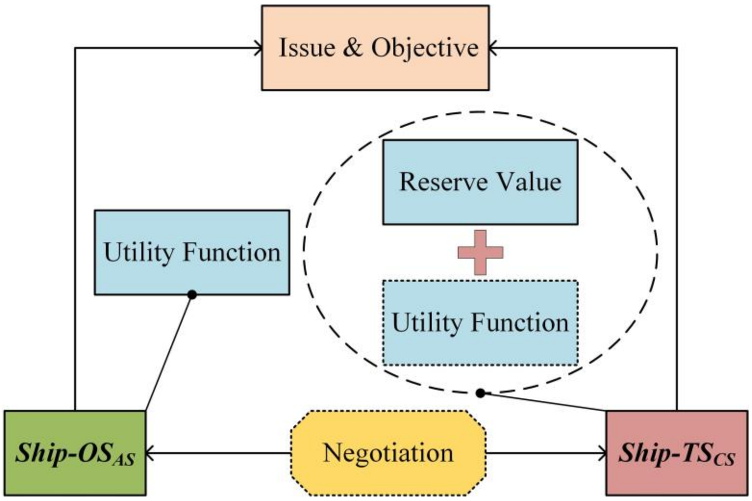


Fig. 2 Organizational structure of collision avoidance negotiation

2.1.1 Negotiating ships

In mixed navigation conditions, the negotiating parties consist of an Autonomous Ship (AS) and a Conventional Ship (CS), which correspond to Own Ship (OS) and Target Ship (TS). According to COLREGs, these vessels take on the responsibilities of either give-way or stand-on roles. For efficient negotiation, the AS functions as the initiator, performing calculation and decision processes, while the CS replies through basic

AIS/VDES messaging. This asymmetric arrangement utilizes the computational capacity of the AS and reduces the technical burden on the CS, thereby facilitating feasible and cooperative collision-avoidance operations.

The preliminary basis for identifying negotiation candidates is the existence of a collision risk. At time t, any vessel within a 6-nautical-mile radius of the OS that simultaneously satisfies Eq. (1) and Eq. (2) is considered a potential negotiation target. Here, $DCPA_{OS-TS}(t)$ and $TCPA_{OS-TS}(t)$ represent the Distance at Closest Point of Approach and the Time to Closest Point of Approach between OS and TS at time t, respectively. SDA (Safe Distance of Approach) denotes the minimum safe distance during an encounter. In this study, considering open-sea conditions, the SDA is set to 1 nautical mile for vessel encounters:

$$DCPA_{OS-TS}(t) < SDA \tag{1}$$

$$TCPA_{OS-TS}(t) > 0 \tag{2}$$

2.1.2 Negotiation issues and objectives

The negotiation issue is central to ship-to-ship collision avoidance, aiming to reach consensus on course adjustments under collision risks. In mixed navigation, it must reconcile COLREGs requirements with uncertainties arising from vessel heterogeneity. For the autonomous ship, the issue is formalized as a collision avoidance plan: assessing risk, identifying encounter type, and generating an avoidance decision. Since most give-way vessels adopt course-changing maneuvers [35], this study defines the negotiation issue as the course change of the give-way vessel, expressed in Eq. (3), where C_R denotes the current collision risk, E_S the encounter situation, and D_M the avoidance decision:

$$I = (C_R, E_S, D_M) \tag{3}$$

The negotiation objective is to achieve an efficient and safe avoidance agreement. Unlike conventional joint-utility maximization, this study emphasizes a practical goal: enabling ships to reach a safe and economical solution within limited negotiation rounds through communication and compromise. This avoids excessive optimization and suits the constrained resources of conventional ships. The AS adapts via unilateral learning, while the CS contributes through simplified information exchange.

2.1.3 Utility value and reserve value

To quantitatively assess proposed avoidance actions, the negotiation framework requires an evaluative metric of decision quality. For this purpose, a utility function is formulated, with collision risk considered the primary determinant. Within the negotiation model, utility values and reserve values act as the principal quantitative measures, guiding vessel choices and concessions throughout the process. The utility value represents the degree of satisfaction associated with specific collision avoidance decisions. It is expressed as a dimensionless scalar within the range $0 \sim 1$, where higher values correspond to stronger adherence to safety requirements and greater satisfaction. This formulation underscores that vessels must assess the importance of each negotiation issue. As evaluation strategies may differ among vessels, distinct utility functions are required to calculate utility values for individual proposed actions.

In the present study, the utility function is defined from the standpoint of navigational safety and is explicitly constructed only for the Autonomous Ship (AS). During negotiation, the AS approximates the utility function of the Conventional Ship (CS). Using this function, the utility value associated with each candidate action can be determined. The reserve value is defined as the minimum acceptable utility level that a vessel is prepared to adopt in collision avoidance negotiation. For a give-way vessel, the reserve value corresponds to the smallest acceptable heading alteration that reduces collision risk below a predetermined safety threshold. For a stand-on vessel, the reserve value indicates its readiness to undertake limited cooperative maneuvers.

2.1.3.1 Establishing a utility function for autonomous ships

The utility function is closely related to the ship's collision risk level. For the own ship, the utility value is defined as the residual collision risk following a collision avoidance maneuver. Thus, the utility function can be expressed as shown in Eq. (4), where $U_{OS_{AS}}$ represents the utility of the autonomous ship and CRI denotes the overall collision risk between the two ships:

$$U_{OS_{AS}} = 1 - CRI \tag{4}$$

In this study, collision risk was represented through spatial collision risk and temporal collision risk. Spatial collision risk indicates the positional closeness and potential threat of approaching vessels, whereas temporal collision risk accounts for the combined effects of speed, separation distance, and evasive maneuvers. When both components contribute equally to the perceived risk, the overall collision risk CRI can be formulated as Eq. (5), where CR_S and CR_T denote the spatial and temporal collision risks, respectively:

$$CRI = CR_D \times CR_T \tag{5}$$

DCPA (Distance at Closest Point of Approach) and TCPA (Time to Closest Point of Approach) are widely recognized as intuitive and essential indicators for evaluating spatial and temporal encounter risks. Assuming the spatial collision risk is bounded by an upper safety threshold d_1 and a lower threshold d_2: d_1 is the distance below which ships are considered to be in imminent collision danger, and d_2 is the minimum range at which spatial collision risk assessment begins. When the actual DCPA lies between d_1 and d_2, the spatial collision risk can be modeled using a sigmoid function due to its monotonic and bounded nature, which allows smooth transition mapping from 1 to 0. By adjusting the steepness parameter λ, the curve's transition can be controlled. Therefore, the spatial collision risk CR_S can be expressed as Eq (6), where $\frac{d_1+d_2}{2}$ represents the midpoint of the transition interval:

$$CR_S = \begin{cases} 1, |DCPA| < d_1 \\ \dfrac{1}{1+e^{\lambda(|DCPA|-\frac{d_1+d_2}{2})}}, d_1 \le |DCPA| \le d_2 \\ 0, d_2 < |DCPA| \end{cases} \tag{6}$$

Assume that in the modeling of temporal collision risk, assume that the upper and lower bounds of the time-based safe encounter interval are denoted as t_1 and t_2, respectively. If the TCPA between the two ships satisfies $TCPA < t_1$, the temporal collision risk is defined as 1, indicating immediate danger. Conversely, if $TCPA > t_2$, the temporal collision risk is defined as 0, indicating no immediate threat. Analogous to spatial modeling, the temporal collision risk CR_T is constructed as Eq. (7):

$$CR_T = \begin{cases} 1, 0 \le TCPA < t_1 \\ \dfrac{1}{1+e^{\lambda(TCPA-\frac{t_1+t_2}{2})}}, t_1 \le TCPA \le t_2 \\ 0, TCPA > t_2 \end{cases} \tag{7}$$

Considering factors such as ship maneuverability, COLREGs requirements, and practical navigation behaviors, 1 nautical mile is generally recognized as the minimum distance to avoid close-quarters situations between merchant ships. Therefore, $d_1 = SDA = 1\ n\ mile$, and $d_2 = 2 * d_1 = 2\ n\ mile$ can reflect security redundancy and layered response design. Accordingly, we define $t_1 = 6mins = 1/10h$ and $t_2 = 18mins = 3/10h$, which are consistent with operational practices of marine ARPA systems in open seas. These parameter values are chosen to balance practical navigation standards with mathematical tractability, ensuring interpretability and sensitivity in real-world encounters. Through multiple parameter-fitting experiments, the function exhibits optimal responsiveness and interpretability when the steepness parameter is set to 16. The resulting temporal collision risk function provides a smooth and sensitive transition between risk states, as illustrated in Fig. 3.

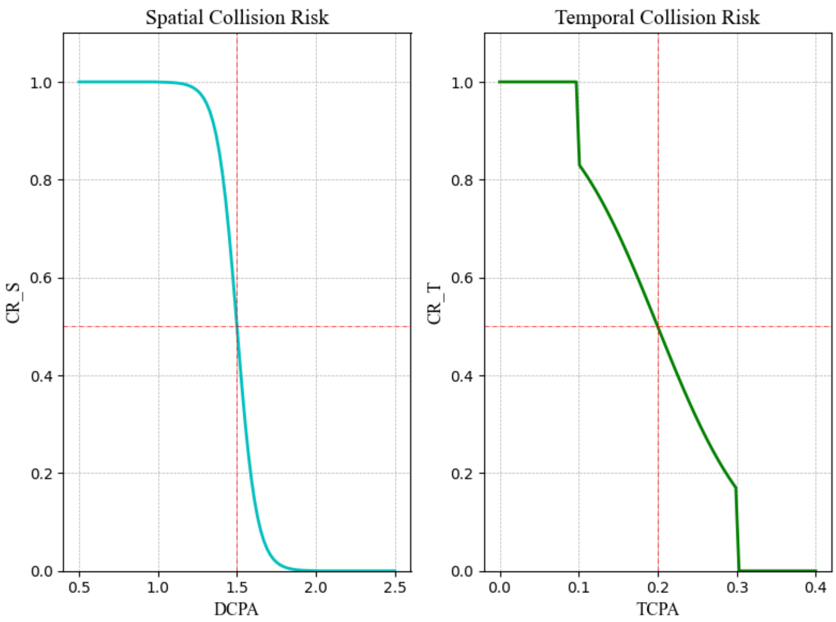


Fig. 3 Ship spatial collision risk and temporal collision risk

2.1.3.2 Estimating the utility function of conventional ships

The utility function reflects the decision maker's evaluation of expected losses or gains under a given scenario and implicitly incorporates their risk preference. In the utility function of the autonomous ship, the threshold value quantifies its risk attitude. For conventional ships, risk preferences can typically be categorized into risk-seeking, risk-neutral, and risk-averse, corresponding to concave, linear, and convex utility functions, respectively, as illustrated by curves *b*, *a*, and *c* in Fig. 4.

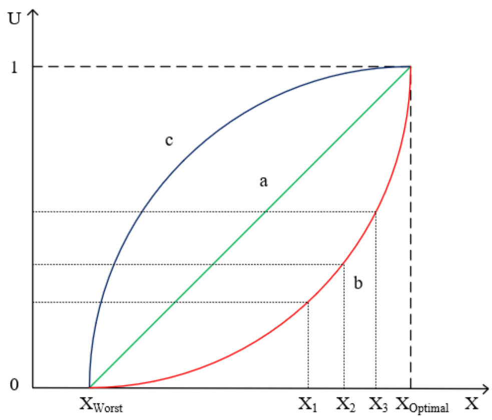


Fig. 4 Utility curves under different risk preferences

However, since the own ship cannot determine the TS's risk preference prior to negotiation, a linear utility function representing risk neutrality is chosen for approximation. The utility function of the conventional ship is defined in Eq. (8), where *x* denotes a single proposal, and the parameters *k* and *b* are determined during the negotiation process based on the TS's first proposal and the OS's estimation of the reserve value of TS:

$$U_{TS_{CS}} = kx + b \tag{8}$$

Let the TS's first proposal be denoted as $X_{Optimal}$, which is assumed to represent its optimal offer and hence corresponds to the maximum utility value. This defines the first coordinate point $(X_{Optimal}, 1)$.According to the loss aversion effect in Prospect Theory, the utility at the reserve value point is typically less than 1, reflecting dissatisfaction with a "barely acceptable" solution. Generally, the utility at the reserve value is set to 0.6, defining a second point $(X_{RV}, 0.6)$. From these two points, the slope *k* and intercept *b* of the linear utility function can be computed, yielding an explicit form of the TS's approximated utility function. This function is then used to calculate utility values for subsequent proposals, which in turn serve as key inputs for the negotiation strategy.

2.2 Procedural model

Following the organizational model, the next stage is the procedural model, which defines the manner in which ships exchange information and interact to achieve consensus. This stage incorporates the communication mechanism, protocol, and a turn-based bidding sequence. In this study, a simplified procedural framework is introduced, emphasizing three essential elements: the negotiation communication mechanism, the negotiation protocol, and the negotiation strategy, with the aim of fostering effective cooperation between autonomous and conventional vessels. The framework is designed to ensure convergence toward a collision avoidance agreement within a finite number of negotiation rounds. This is achieved by employing a standardized communication mechanism to guarantee clarity and interoperability of messages, a turn-based bidding protocol to structure vessel interactions, and a game-theoretic strategy to adjust proposals dynamically according to utility values and the observed behavior of the counterpart. Such a design enables efficient and practical negotiation within the real-time demands of maritime operations.

2.2.1 Negotiation communication mechanism

The negotiation communication mechanism forms the foundation for information sharing and interaction between vessels, ensuring efficient and accurate transmission of collision avoidance information between autonomous and conventional ships in mixed navigation scenarios. Drawing on Speech Act Theory, a structured communication mechanism for negotiation is proposed. In this mechanism, the information necessary for collision avoidance is encapsulated into a structured information set, denoted as $Data = \$Primitive : Content\$$. This set consists of two parts: primitives and content.

Communication primitives standardize the communication process and describe the basic interactive actions during negotiation. The primitives defined in this study cover the entire process of communication, as shown in Table 1. Each primitive is designed to be executed within a single communication process, maintaining clarity and structure. Ultimately, the overall communication is formed through multiple such processes.

The content includes information related to collision avoidance, which is comprised of keywords and values, and it can be represented as $Communication\ content = Keyword(Value)$. Definitions and explanations are shown in Table 2. Naturally, a message can contain more than one keyword, thus the content of negotiation communication can also be defined as $Communication\ content = Keyword_1(Value_1) \cdots Keyword_n(Value_n)$. For instance, if OS wants to inform the TS of the encounter situation and the upcoming collision avoidance method, the message can be:

$Inform:MANOEUVRE(TURNPORT)\,STEERINGANGLE(15)\,ACTIONTIME(5)$. The meaning is to inform TS that she needs to turn the port 15° in 5 min.

Table 1 Definition of negotiation communication primitives

Number	Primitive	Requirement	Reply	Explanation
1	Begin	Null	Yes	Initiating a new process
2	End	Null	Yes	Terminating the current process
3	Ack	Null	No	Acknowledging message receipt
4	Disagree	Information or data	Yes	Disagreeing counterpart's proposal
5	Doubt	Null	Yes	Expressing uncertainty and seeking clarification
6	Accept	Null	Yes	Agreeing to the request or proposal and closing the process
7	Reject	Null	No	Refusing the request or proposal and closing the process
8	Verify	Information	Yes	Seeking to confirm certain details
9	Inform	Information or data	Yes	Sharing general information
10	Advise	Suggestion	Yes	Offering suggestions
11	Request	Command	Yes	Making a strong demand

Table 2 The definition of negotiation communication content

Keywords	Type and value
NAME	String
COURSE	Numeric: 0°~360°
POSITION	Numeric: Longitude $\pm 180^{\circ}$ and Latitude $\pm 90^{\circ}$
RESPONSIBILITY	Enumerable: {Give-way, Stand-on}
SITUATION	Enumerable: {HEAD-ON, CROSSING, OVERTAKING}
MANOEUVRE	Enumerable: {TURNPORT, TURNSTARBOARD, KEEP COURSE}
STEERINGANGLE	Numeric: $0^{\circ} \sim 45^{\circ}$
ACTIONTIME	Numeric: $0 \sim 99$ *minutes*

2.2.2 Negotiation communication protocol

The negotiation protocol establishes the rules and procedures that regulate vessel interaction, aiming to achieve adaptive adjustment of collision avoidance decisions through a turn-based bidding framework. In this study, a protocol inspired by alternating offers is introduced, simulating a maritime "call-and-response" pattern to provide both fairness and flexibility during negotiation.

As shown in Fig. 5, the process begins with the Autonomous Ship (OS) presenting an initial proposal for a collision avoidance maneuver. The Target Ship (TS) subsequently replies with its own proposal, thereby completing a single negotiation round. If agreement is not obtained, the OS modifies its proposal according to the feedback received. The TS may either retain its previous offer or submit a revised proposal, and this sequence repeats until consensus is reached.

This protocol is especially suitable for mixed navigation conditions, as it reflects the customary communication style of conventional ship operators and reduces technical challenges for traditional vessels to engage in negotiation. The structured bidding approach allows vessels to iteratively refine their proposals, achieving a compromise between safety and efficiency without dependence on unilateral actions or resource-intensive optimization processes.

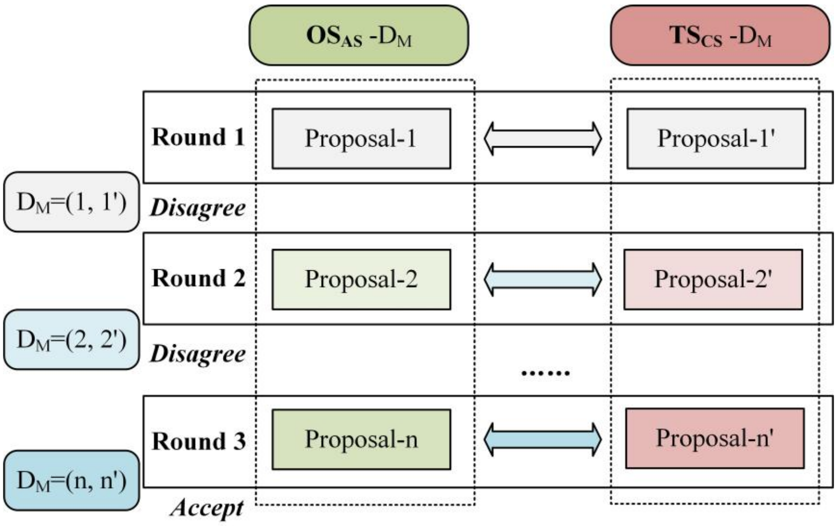


Fig. 5 Proposal process based on the bargain protocol

2.2.3 Negotiation communication strategy

Under the turn-based bidding framework, the autonomous ship assesses the conventional ship's proposal by verifying compliance with COLREGs and confirming that DCPA/TCPA values remain above predefined safety limits. To manage the concession process, the Zeuthen unidirectional strategy is applied in this study, ensuring continuity of negotiation without requiring complete information about the opponent's utility. Both vessels start with favorable offers and progressively concede according to rational evaluations of risk.

The strategy introduces two central measures: Maximum Risk Tolerance (MRT), defined as the ratio between the utility loss incurred by accepting the counterpart's proposal and the loss resulting from negotiation failure, and Minimum Concession Magnitude (MCM), which specifies the smallest concession necessary to alter the negotiation balance. Combined, these principles regulate the timing and scale of concessions, facilitating convergence while maintaining fairness and transparency.

The Zeuthen strategy provides clear rules for determining the appropriate response to an opponent's offer. The concession rule is formalized by comparing the relative risk of maintaining one's proposal versus accepting the opponent's proposal. MRT guides how to formulate the next proposal by applying a concession, as shown in Eq. (9), where $U_i(P_i^t)$ is the utility of ship i at round t, $U_i(P_j^t)$ is the utility if the opponent's proposal is accepted, and $U_i(\text{Failure}) = 0$ is the utility in case of negotiation failure (typically 0):

$$MRT_i = \frac{U_i(P_i^t) - U_i(P_j^t)}{U_i(P_i^t) - U_i(\text{Failure})} \tag{9}$$

In round t, the MRT values for the OS and the TS are computed as in Eq. (10) and Eq. (11), where U_{aa}^i and U_{ca}^i represent the utilities of the autonomous and conventional ships proposed in round t, U_{cc}^i and U_{ac}^i represent the utility of conventional ships and autonomous ships under the proposal of conventional ships in round t. Since failure utilities are assumed to be 0, they are omitted from the denominator:

$$MRT_a^i = \frac{U_{aa}^i - U_{ac}^i}{U_{aa}^i - U(a)} = \frac{U_{aa}^i - U_{ac}^i}{U_{aa}^i} \tag{10}$$

$$MRT_c^i = \frac{U_{cc}^i - U_{ca}^i}{U_{cc}^i - U(c)} = \frac{U_{cc}^i - U_{ca}^i}{U_{cc}^i} \tag{11}$$

A valid concession modifies the distribution of risk and guarantees that each adjustment effectively promotes negotiation convergence. The vessel with the smaller MRT is required to concede by revising its proposal. The MRT mechanism functions as the governing rule for concessions, as expressed in Eq. (12):

$$\left.\begin{array}{l} MRT_a^i > MRT_c^i, CS\ make\ concessions \\ MRT_a^i = MRT_c^i, AS\ and\ CS\ make\ concessions\ or\ reach\ a\ consensus \\ MRT_a^i < MRT_c^i, AS\ make\ concessions \end{array}\right\} \tag{12}$$

If $MRT_a^i < MRT_c^i$, then OS concedes; otherwise, TS should be prompted to concede. When both parties exhibit equal MRT values, they may proceed to finalize the agreement or initiate additional rounds for finer negotiation.

The use of the Zeuthen strategy in ship collision avoidance negotiation is depicted in Fig. 6. In this process, the OS initiates a proposal and subsequently receives a counter-proposal from the TS. The OS then estimates the reserve value and utility function of the TS, recalculates the MRT values for both parties, and determines whether the TS's offer should be accepted. If the MRT values are equal or sufficiently close, the negotiation is concluded. Otherwise, the OS decides which party should make a concession. When the OS concedes, the magnitude of concession is calculated and a new proposal is generated; if the concession is expected from the TS, the OS initiates communication through the prescribed messaging protocol. The introduction of the Zeuthen strategy into mixed navigation contexts provides a means of resolving challenges associated with information asymmetry and decision heterogeneity. In contrast to fixed-rule or optimization-based methods, the dynamic concession mechanism of the Zeuthen strategy accommodates varying risk preferences, maintains fairness, and facilitates agreement within a limited number of negotiation iterations.

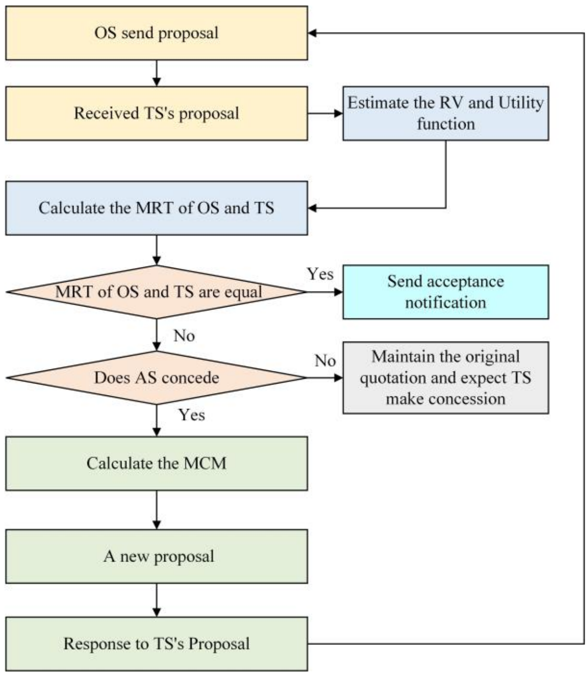


Fig. 6 Application of Zeuthen strategy in negotiation

2.3 Unilateral learning

2.3.1 Bayesian rule and Bayesian learning

As the final component of the procedure, unilateral learning enables the autonomous ship to refine its understanding of the conventional ship's behavior, using Bayesian inference to update utility estimates and improve negotiation convergence. Traditional statistical methods require distribution assumptions, while machine learning demands large datasets-both impractical in dynamic navigation. Bayesian learning addresses this by iteratively updating probability estimates, combining prior knowledge with new data. Through Bayesian inference, the OS refines estimates of the TS's reserve value and utility function, enabling more accurate counter-proposals. This probabilistic reasoning enhances adaptability and supports rational decision-making in collision avoidance.

Eq. (13) provides a method for calculating the posterior probability $P(h|D)$ from the prior probability $P(h)$, $P(D)$ and the conditional probability $P(D|h)$. $P(h)$ is the prior probability of event h, $P(D)$ is the prior probability of training data D, $P(D|h)$ is the conditional probability, and $P(h|D)$ is the posterior probability of event h:

$$P(h|D)=\frac{P(D|h)P(h)}{P(D)} \tag{13}$$

2.3.2 Bayesian learning method in negotiation

The autonomous ship, as the learner, infers the conventional ship's reserve value-a key negotiation parameter-via probabilistic estimation. Prior knowledge from historical data or assumptions initializes a probability distribution. Iterative negotiations employ conditional probabilities to assess proposal likelihoods under hypothetical reserve values, updating the posterior distribution through Bayesian inference for improved opponent modeling and strategic adaptation.

The learning objective is the estimation of the utility function of the TS, achieved by updating its reserve value. The reserve value represents an estimate of the TS's actual maneuvering after negotiation. The prior knowledge of the OS includes: the initial estimation of the TS's reserve value range, denoted as $RVR=\{r_1,r_2,...,r_n\}$, the probability distribution of the reserve value, denoted as $p(r_i)$, and the conditional probability of the TS's proposal under the OS's assumption, denoted as $p(q_i|r_i)$ (the probability of proposing q_i for each r_i). After receiving a new proposal from the TS, the Bayesian learning mechanism updates the OS's estimation of prior knowledge.

Assuming the proposal of TS is q_1, the probability distribution of its reserve value is updated as Eq (14):

$$p(r_i|q_1)=\frac{p(r_i)*p(q_1|r_i)}{\sum_{i=1}^{n}p(q_1|r_i)*p(r_i)} \tag{14}$$

The estimated reserve value of TS is updated as Eq. (15):

$$RV(q_1)=\sum_{i=1}^{n}r_i*p(r_i|q_1) \tag{15}$$

Fig. 7 shows that in the negotiation process of Round i, after receiving the proposal from TS, OS updates the probability distribution of the reserve value for TS based on this information. This updated distribution also constitutes OS's prior knowledge in the next negotiation Round $i+1$.

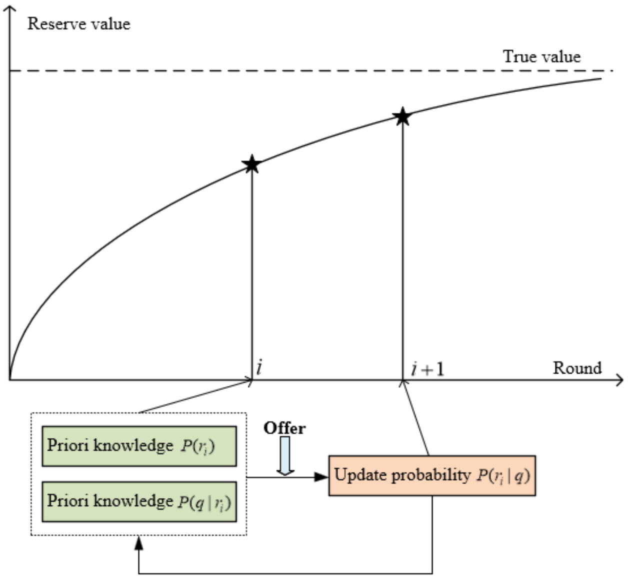


Fig. 7 Bayesian learning mechanism in ship collision avoidance negotiation

2.3.3 A unilateral learning model based on the Zeuthen strategy

The unilateral learning model for ship collision avoidance negotiation, developed on the basis of the Zeuthen strategy, is illustrated in Fig. 8. The model requires as inputs the utility function of the OS and prior knowledge regarding the reserve value of the TS. Its outputs include the Zeuthen negotiation solution x^*_{slt}, and the corresponding sequence of proposals. These proposals allow the OS to employ a Bayesian learning framework in successive rounds, thereby refining the estimation of the TS's negotiation preferences and utility function.

When a proposal is received from the TS, the OS applies Bayesian inference to update the estimated utility function of the TS, recalculates the MRT values of both parties, and decides whether concessions should be made. The TS, acting as the conventional vessel and operationally represented by the OOW, then determines whether to concede and the extent of such concessions, guided by the evaluation of collision risk, interpretation of the opponent's intentions, and situational judgment during the negotiation process.

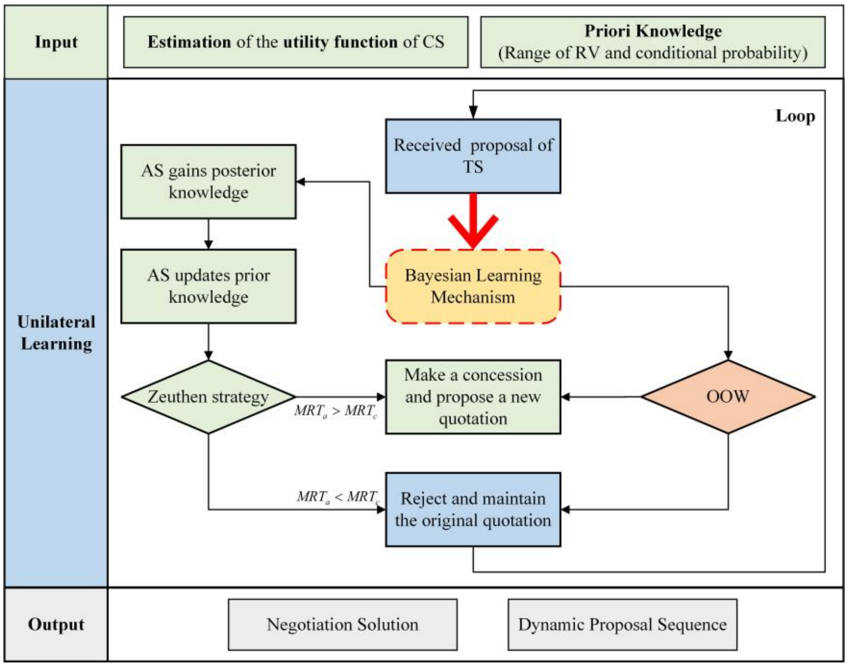


Fig. 8 Unilateral learning model for negotiation based on Zeuthen strategy

3. Application and validation

In our previous research, the proposed ship collision avoidance decision-making algorithm, which incorporates multiple navigational constraints, was tested using an electronic nautical chart platform [4]. Within the test scenarios, a portion included uncoordinated avoidance actions, where the TS either breached COLREGs or undertook maneuvers that created conflict. For validation of the model and method developed in this study, a representative uncoordinated crossing encounter was selected, in which the TS acted as the give-way vessel but did not execute the required maneuver.

The following objective facts and assumptions were established for the validation study:

(1) The negotiation is led by the OS, functioning as the autonomous ship. OS controls the negotiation flow but does not infringe upon the interests of TS, the conventional ship.

(2) During negotiation, OS has knowledge of its own utility function and reserve value, while the corresponding parameters for TS must be inferred through learning and approximation.

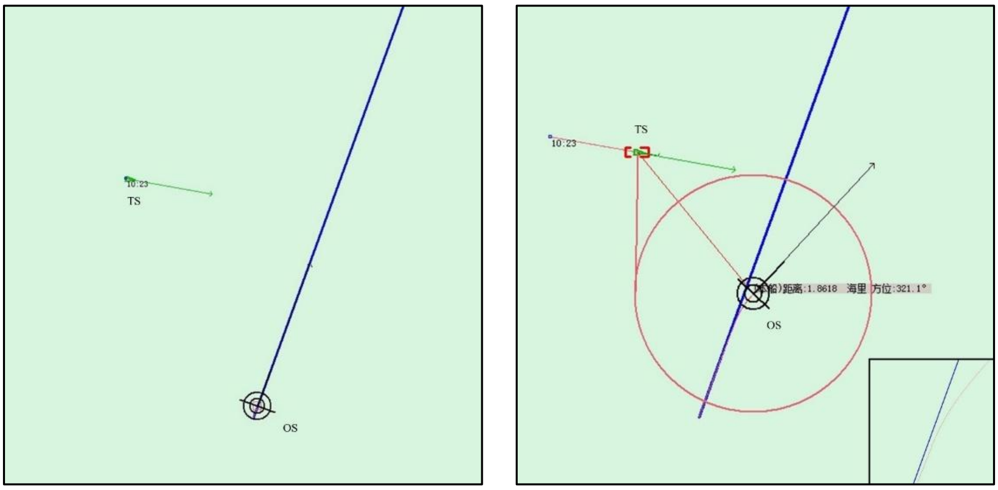
(3) The prior knowledge of OS regarding TS's behavior is based on findings from previous literature, specifically for crossing encounter scenarios.

(4) OS's decision-making is powered by a modified VO algorithm [5], which identifies the set of velocities that would lead to a collision with TS within a given time horizon, and ensures that the selected maneuver remains outside this collision set, implemented within our research team's autonomous ship simulator. Decisions of the conventional ship are generated by a licensed Captain within the team.

3.1 Scenario 1: Crossing encounter situation (TS as give-way vessel)

In this study, we referred to the statistical research of Zheng [35]. He provided the distribution of the steering angle of the give-way vessel when the speed of the stand-on vessel is 20 knots and the speed of the give-way vessel is 15 knots, and the stand-on vessel is located 30° to the starboard side of the give-way vessel in a crossing encounter situation. Based on this, this study referred to the opinions of captains with recent sailing experience for correction.

In this scenario, OS and TS are engaged in a crossing encounter, with OS approaching from the starboard side of TS, as shown in Fig. 9(a). Initial parameter settings are listed in Table 3. According to COLREGs, TS is obligated to give way, but fails to take any action, resulting in an uncoordinated avoidance situation. Under general autonomous avoidance strategies, OS would proactively maneuver to avoid TS, as illustrated in Fig. 9(b). However, in this study, OS attempts to negotiate collision avoidance with TS, aiming to avoid unnecessary give-way action, thereby reducing maneuvering effort and minimizing route deviation.



(a) Initial encounter situation (b) CA manoeuvre

Fig. 9 Initial encounter situation of scenario 1

Table 3 Information about the initial encounter situation

Ship	Position	Heading (degree)	Speed (knot)	Distance (n mile)	True Bearing (degree)
OS(AS)	(19°48′36″, 127°9′36″)	022	18	/	/
TS(CS)	(19°51′36″, 127°9′11″)	100	12	3.14	330.62

3.1.1 Prior knowledge estimation

To enable effective negotiation, OS must estimate both the possible values of TS's reserve value and the conditional probability of TS's decisions under given conditions, based on collision avoidance knowledge.

(1) Estimation of the reserve value of the conventional ship

In common crossing encounter situations, no strict regulatory restrictions exist regarding the extent of course alterations a vessel may undertake to prevent collisions. Nevertheless, the probability of selecting different magnitudes of heading changes is not uniform. Small-angle adjustments are more frequently adopted, as they reduce collision risk while causing minimal deviation from the intended route and conserving fuel. Moderate-angle alterations are considered reasonable and are generally used when a more evident evasive response is necessary. Large-angle alterations are uncommon and are typically applied only in emergencies, as they can promptly eliminate collision threats but may adversely influence vessel stability and subsequent route planning.

In this study, large-scale AIS historical data were examined to identify typical evasive actions during crossing encounters. Furthermore, consultations with experienced captains were conducted to refine these findings. Through the integration of empirical evidence and expert judgment, a probability distribution table was developed to represent the likelihood of various heading change magnitudes. In the testing framework, the OS assigns each candidate course alteration value r for the TS a probability estimates $p(r)$, which reflects OS's assessment of the TS's reserve value. The corresponding probabilities are provided in Table 4. For heading values positioned between the listed data points, interpolation is applied to approximate the probability values.

Table 4 Estimation of the reserve value of TS by OS

Reserve Value	r_1	r_2	r_3	r_4	r_5	r_6	r_7
Course change r_i	15	20	30	40	50	60	70
Probability $p(r_i)$	0.08	0.10	0.35	0.30	0.10	0.05	0.02

Based on prior knowledge, the OS estimates the reserve value of the TS prior to negotiation as Eq (16):

$$RV_{TS0} = \sum r_i \times p(r_i) = 35.1 \tag{16}$$

(2) Estimation of TS's possible decisions

Based on the reserve value estimation, the OS must further predict the proposal that the TS is likely to present under this assumption. This process represents the OS's anticipation of the TS's negotiation approach. From the perspective of collision avoidance, it is assumed that when the TS has a predetermined expected heading adjustment and participates in negotiation, it will propose a value that lies within a reasonable interval around its reserve value. The conditional probability principle indicates that the TS is most likely to suggest a heading change slightly lower than its reserve value, thereby conserving maneuvering effort while still satisfying safety requirements. The probability of proposing values considerably higher or lower than the reserve value is minimal, as such actions either involve unnecessary deviation or fail to achieve adequate safety. Based on previous scholarly research and the experience of captains, the conditional probability distribution was established, as shown in Table 5. This framework illustrates the bounded rationality and risk-averse behavior of human operators on conventional vessels, particularly under uncertain negotiation conditions.

Table 5 The conditional probability of TS's decision

Assumption		Probability							
		q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8
		5	10	15	20	30	40	50	60
r_1	15	0.10	0.75	0.10	0.05	0	0	0	0
r_2	20	0.10	0.15	0.60	0.10	0.05	0	0	0
r_3	30	0.05	0.10	0.30	0.45	0.05	0.05	0	0
r_4	40	0	0.05	0.10	0.30	0.45	0.05	0.05	0
r_5	50	0	0	0.05	0.10	0.30	0.45	0.05	0.05
r_6	60	0	0	0	0.05	0.10	0.30	0.50	0.05
r_7	70	0	0	0	0	0.05	0.15	0.30	0.50

3.1.2 The decision-making and calculation process of negotiation

3.1.2.1 First round of negotiation

In the first round, under the initial encounter condition, OS proposes a starboard maneuver of 40.6°, which is the result of its autonomous collision avoidance algorithm. Upon receiving this proposal, TS responds with a counter-proposal of 30° (q_5=30). Based on the prior probability distribution and TS's actual proposal, OS updates its estimation of TS's reserve value, obtaining 40.8. The specific calculation process is provided in Appendix A.

(1) Estimating the utility function of the conventional ship

As previously discussed, the estimated utility function of TS can be defined as a function of the heading change *x*. Using Eq. (17), OS can compute TS's utility under different proposal values:

$$U_{TS_{CS}1} = 1-(1-U_{X_{RV}})*\frac{x-X_{Optimal}}{RV_{TS1}-X_{Optimal}} = 1-(1-0.6)*\frac{x-30}{40.8-30} = 2.11-0.037x \tag{17}$$

(2) Calculating Maximum Risk Tolerance (MRT)

Let U_{ac}^{1} and U_{ca}^{1} represent the utilities of OS and TS when accepting the opponent's proposal. The MRT values of the ships in this round can be calculated using Eq. (18) and Eq. (19):

$$MRT_{OS}^{1} = \frac{U_{aa}^{1}-U_{ac}^{1}}{U_{aa}^{i}-U(a)} = \frac{1-0.6078}{1-0} = 0.3922 \tag{18}$$

$$MRT_{TS}^{1} = \frac{U_{cc}^{1}-U_{ca}^{1}}{U_{cc}^{i}-U(c)} = \frac{1-0.1276}{1-0} = 0.8724 \tag{19}$$

Since OS is identified as the party with the lower MRT, it must concede. Otherwise, OS would initiate a communication act, requesting TS to make a concession.

(3) Determining the concession magnitude

Unlike negotiation domains where large margins and long cycles are acceptable, maritime collision avoidance occurs under strict time constraints and small proposal differences. In real-world navigation, mutual consensus is typically reached within two rounds of communication. Considering these constraints and the characteristics of mixed navigation scenarios, a three-round negotiation limit is assumed. To ensure timely convergence: The first-round concession is set as one-third of the initial proposal gap; The second-round concession is set as one-half of the current proposal gap; If the proposal difference is within 20% of the original proposal gap, OS will accept the TS's offer. Accordingly, in the second round, OS updates its proposal to 37°.

3.1.2.2 Subsequent negotiations

In the second round, OS repeats the same analysis steps as in the first round: updating the probability distribution of TS's reserve value, estimating TS's utility function, and calculating MRT values for both ships. TS responds with a revised proposal of 33°. OS again updates its probability distribution for TS's reserve value, as shown in Table 6, and applies linear interpolation to calculate the conditional probability (q = 33°). The updated reserve value and utility function are then used to recalculate MRT.

Since OS again has the lower MRT, it concedes with a 2° adjustment, yielding a third-round proposal of 35°. Upon receiving this proposal, TS accepts, and the negotiation concludes. The detailed calculation process is shown in Appendix B.

Table 6 The conditional probability of TS's decision under the assumption of OS (Round 2)

Assumption		Probability							
		q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8
		5	10	15	20	30	40	50	60
r_1	15	0.10	0.75	0.10	0.05	0	0	0	0
r_2	20	0.10	0.15	0.60	0.10	0.05	0	0	0
r_3	30	0.05	0.15	0.25	0.40	0.10	0.05	0	0
r_4	40	0	0.05	0.15	0.25	0.40	0.10	0.05	0
r_5	50	0	0	0.05	0.10	0.30	0.45	0.05	0.05
r_6	60	0	0	0	0.05	0.10	0.30	0.50	0.05
r_7	70	0	0	0	0	0.05	0.15	0.30	0.50

3.1.2.3 Final Outcome and reaching a consensus

After three negotiation rounds, the two ships reach an agreement at a heading change of 35°. The proposal sequence is summarized in Table 7 and Fig. 10. The negotiation, guided by the Zeuthen strategy, shows that both parties began with their most favorable proposals and gradually made concessions toward the other. Consensus was reached in a short negotiation window, reflecting both rational decision-making and practical feasibility. Moreover, validation results confirm that at the final agreement point, both parties' MRT values had converged significantly, indicating a mutually acceptable and safe decision. Notably, in all rounds, the agreed solution remained within the estimated interval of TS's reserve value as inferred by OS. This is consistent with real-world maritime communication, where negotiation outcomes typically remain within reasonable bounds to ensure navigational safety.

Table 7 Proposal sequence for negotiation

	OS's proposal	TS's proposal	Estimated value of RV	Concession
Preparation stage	/	/	35.1	/
Round 1	40.6	30	40.8	OS
Round 2	37	33	41.1	OS
Round 3	35	35	/	/

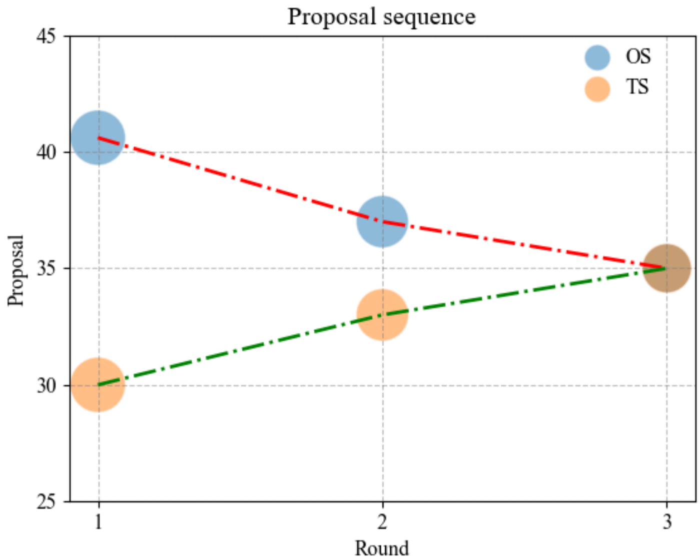


Fig. 10 The process of negotiating proposals

3.1.3 The communication process of negotiation

In earlier research, the application of the proposed model was demonstrated through algorithmic implementation and case analysis. To provide a more intuitive representation of the negotiation process, this section describes the communication flow based on the negotiation protocol defined earlier.

As shown in Fig. 11, OS initiates the negotiation. TS replies with an Ack message, indicating its willingness to engage. At this stage, the negotiation channel between the two ships is established. First, OS sends a Verify message to TS to confirm the current encounter situation, as expressed in Eq. (20):

$$Verify: SITUATION(CROSSING)RESPONSIBILITY(Give-way) \tag{20}$$

Upon receiving this message, TS raises no objection and responds with Ack. Subsequently, OS initiates negotiation on the collision avoidance decision, and the following communication exchange takes place. Given the need to conclude negotiations quickly, the tone and intent of OS's messages escalate progressively—from Advise to Inform, and finally to Request—reflecting the increasing urgency of the situation. To reduce communication overhead, both parties exchange only information regarding points of disagreement. Any information not mentioned in subsequent messages is implicitly accepted. The communication process is represented in Eq. (21) to Eq. (26):

$$Advise: NAME(TS)MANOEUVRE(TURNSTARBOARD)STEERINGANGLE(40.6) \tag{21}$$

$$Disagree: STEERINGANGLE(30) \tag{22}$$

$$Inform: STEERINGANGLE(37) \tag{23}$$

$$Disagree : STEERINGANGLE(33) \tag{24}$$

$$Request : STEERINGANGLE(35) \tag{25}$$

$$Accept : STEERINGANGLE(35) \tag{26}$$

Once mutual agreement is achieved, OS issues an End message to formally close the negotiation. TS acknowledges the termination by replying with Ack. This structured communication flow ensures clarity, conciseness, and efficiency of ship-to-ship negotiation under time-sensitive maritime collision avoidance scenarios.

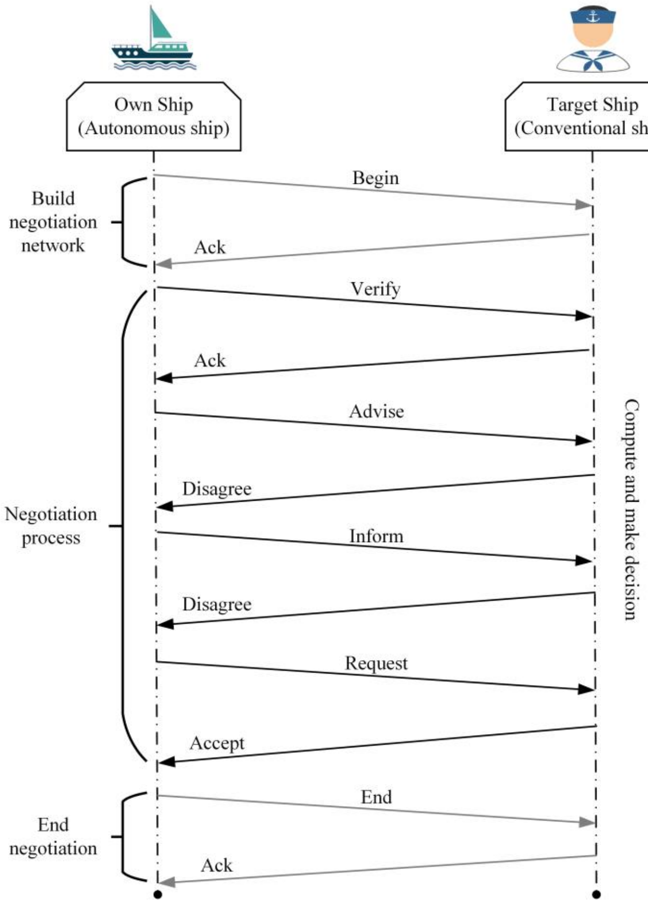


Fig. 11 The negotiation timing diagram

3.1.4 Analysis of negotiation results

Based on the negotiation process and its outcomes, the original encounter scenario was reconstructed to analyze the resulting navigational behavior. Fig. 12 and Fig. 13 depict ship trajectories under different proposal conditions. Fig. 12 shows TS's trajectories when adopting the proposals made by OS across three negotiation rounds: Decision 1 is a 40.6° starboard turn (first-round proposal), Decision 2 is a 37° starboard turn (second-round proposal), and Decision 3 is a 35° starboard turn (third-round and final agreement). Fig. 13 shows TS's trajectories when executing its own proposals during each negotiation round: Decision 1 is a 30° starboard turn, Decision 2 is a 33° starboard turn, and Decision 3 is a 35° starboard turn.

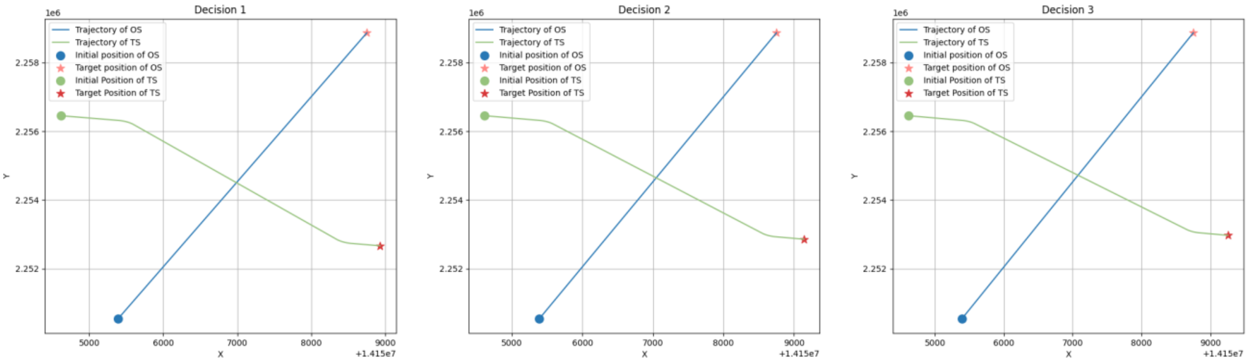


Fig. 12 Negotiated collision avoidance trajectory under the decision proposed by OS

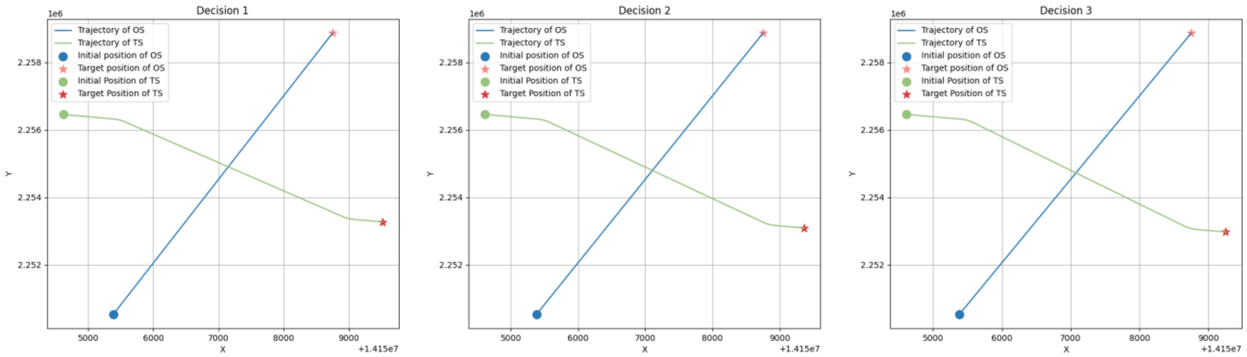


Fig. 13 Negotiated collision avoidance trajectory under the decision proposed by TS

Although the proposed course angles vary between the two ships, each decision remains reasonable and ensures safety. Through negotiation, the original uncoordinated collision avoidance scenario is transformed into a coordinated and secure encounter. To further illustrate the enhancement of safety, Fig. 14 and Fig. 15 show the variation of DCPA under different proposals. Fig. 16 overlays these datasets to reveal the trend of increasing DCPA throughout the negotiation. As the negotiation progresses, the DCPA steadily increases, confirming the effectiveness of the negotiation mechanism in improving collision avoidance safety. It was observed that when proposals were made by the OS, the TS tended to choose larger turning angles (ranging from 40.6° to 35°). In contrast, when the TS acted independently, it selected more moderate maneuvers (ranging from 30° to 35°). In both approaches, however, the DCPA consistently remained above the defined safety margin, confirming the reliability of the negotiated outcomes. The negotiation process encouraged conventional vessels to recognize the role of autonomous ships, while preventing autonomous vessels from being compelled into purely reactive avoidance maneuvers. Through active involvement in negotiation, autonomous vessels were able to maintain their intended navigation plans and minimize unnecessary course deviations.

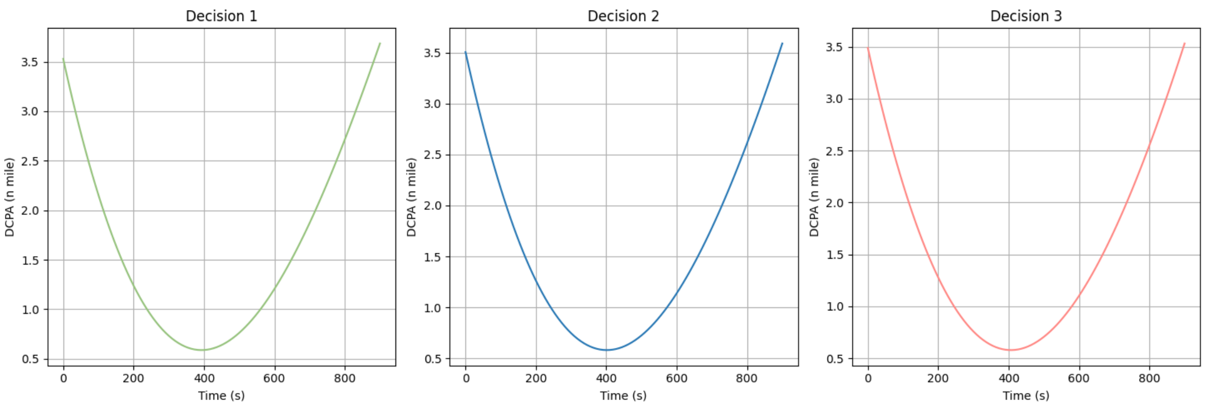


Fig. 14 DCPA variations under the decision proposed by OS

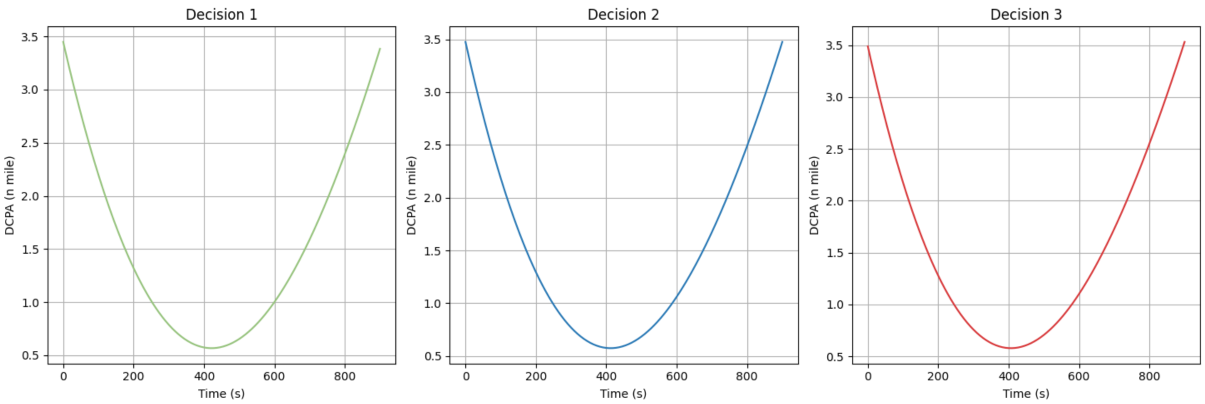
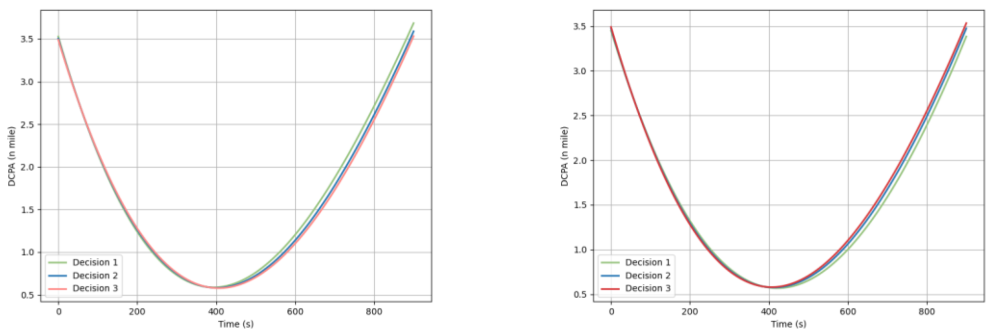


Fig. 15 DCPA variations under the decision proposed by TS



(a) DCPA variations under OS' proposal (b) DCPA variations under TS' proposal

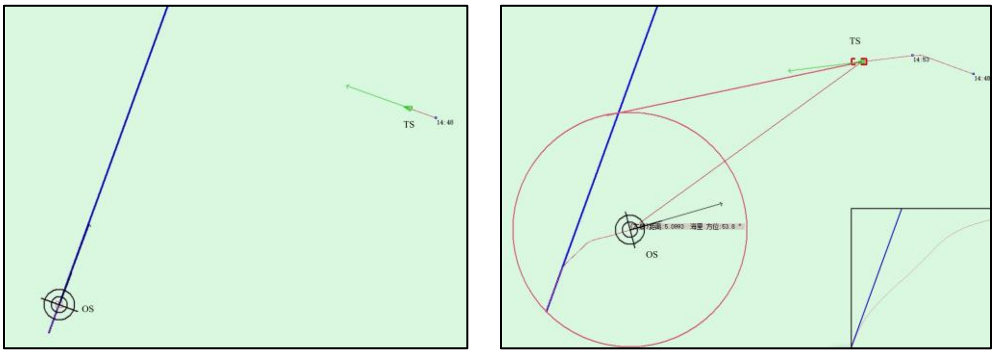
Fig. 16 Comparison of DCPA variations under different proposed decisions

This study successfully demonstrates that the proposed negotiation-based approach can transform a potentially hazardous and uncoordinated situation into a safe and coordinated maritime environment. The method proves to be feasible and effective in mixed navigation scenarios. It not only enhances the collision avoidance capability of ships but also mitigates uncoordinated situations—especially when dealing with conventional vessels that may not strictly follow COLREGs or exhibit low safety awareness. Furthermore, it ensures that autonomous ships retain operational efficiency without excessive maneuvering or route loss.

It should be pointed out that this study focuses on negotiation modes and decision-making processes and does not involve the specific implementation of communication technology. Therefore, the computational complexity of this method only reflects the algorithm level of negotiation and decision-making, rather than the message transmission or communication protocol layer. In our simulation, negotiation usually converges within three rounds, and the computational burden only includes lightweight computing tasks such as utility values, which can usually be completed within 1 second. With the support of communication technology, the method proposed in this article has high real-time performance.

3.2 Scenario 2: Crossing encounter situation (TS as stand-on vessel)

In Scenario 2, OS and TS are in a crossing situation, with TS positioned on the starboard side of OS, as depicted in Fig. 17(a). The initial parameters are listed in Table 8. According to COLREGs, OS, being the give-way vessel, is expected to turn to starboard to avoid collision, with the intention of passing astern of TS. However, TS turns to port for an unknown reason, as shown in Fig. 17(b). This maneuver is clearly non-compliant and creates an uncoordinated collision avoidance situation. To clarify the actions of TS and to adjust the decision-making of OS, negotiation is initiated to reduce the risk of collision and ensure safe passage.



(a) Initial encounter situation (b) CA manoeuvre

Fig. 17 Initial encounter situation of scenario 2.

Table 8 Initial parameters of Scenario 2

Ship	Position	Heading (degree)	Speed (knot)	Distance (n mile)	True Bearing (degree)
OS(AS)	(18°4′12″, 131°40′48″)	020	15	/	/
TS(CS)	(18°8′24″, 131°48′36″)	290	16	8.66	61.23

In this scenario, OS is the give-way vessel and TS is the stand-on vessel. Unlike Scenario 1, where TS was expected to take action but failed to do so, the objective here is to understand TS's true intentions through negotiation. The outcome of negotiation should lead to TS's approval of OS's subsequent maneuver, ensuring that TS does not engage in resistance or conflicting actions.

Through negotiation, OS and TS clarified their encounter situation and respective actions. OS obtained TS's clear intentions, and TS ceased additional course changes, updating its decisions based on previous actions. OS's initial decision was to turn starboard by 23.5°, which was updated to a 53.5° starboard turn after negotiation, adjusting her course to 73.5°. TS raised no objection to this maneuver. Although the decision of the maneuvering vessel was not directly negotiated, the process clarified both parties' intentions, preventing the occurrence of further collision risks.

Fig. 18 reconstructs OS's navigation trajectories before and after updating her decision, where Decision 1 involves a starboard turn of 23.5° and Decision 2 is a 53.5° starboard turn. Fig. 19 shows the corresponding variations of DCPA. It can be observed that Decision 1 results in a very small DCPA, which cannot ensure safe passage, while Decision 2, updated through negotiation, significantly improves safety in this unexpected situation.

In this scenario, the significance of negotiation lies in enabling OS to comprehend the navigation dynamics of TS, even when TS engages in highly uncoordinated maneuvers. This allows OS to fulfill her give-way obligations without frequent interruptions, facilitating a swift response and enabling OS to navigate away from such target ships promptly.

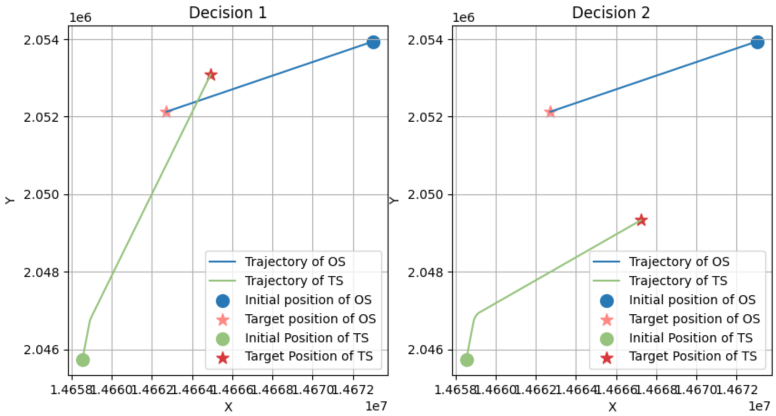


Fig. 18 Negotiated collision avoidance trajectory under the decision proposed by OS

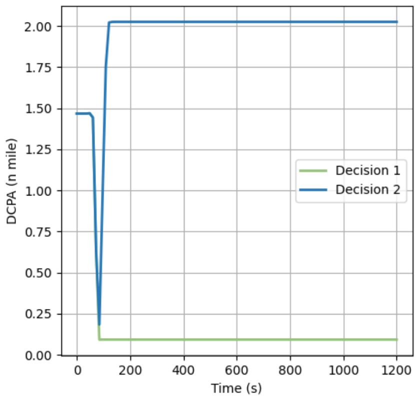
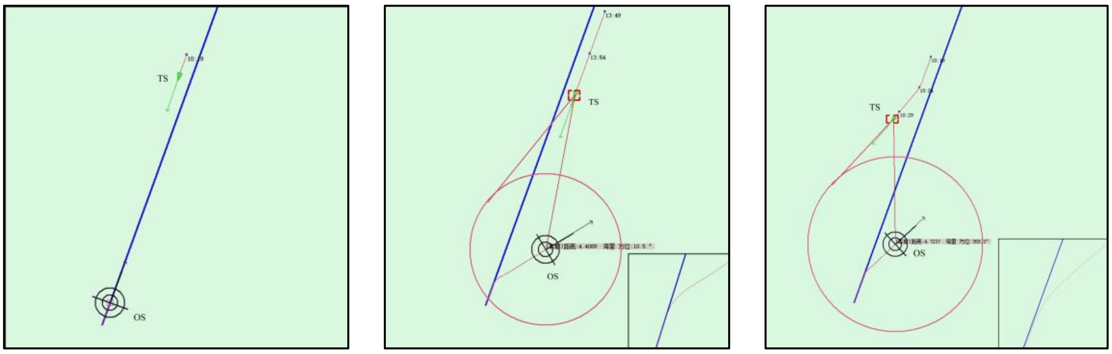


Fig. 19 DCPA variations under the decision proposed by TS

3.3 Scenario 3: Head-on encounter situation

In Scenario 3, the initial encounter is shown in Fig. 20(a), where OS and TS are in a head-on situation with TS on the port side of OS. The initial navigation parameters are provided in Table 9. According to COLREGs, both vessels should turn to starboard. There are two possible scenarios for TS. TS may believe that after OS turns to starboard, no further maneuver is required, and therefore maintains course and speed, as shown in Fig. 20(b). In this case, OS may need to update her decision and execute a larger turn to avoid collision. Alternatively, OS expects TS to fulfill her duty as the give-way vessel and cooperate by also turning to starboard, as illustrated in Fig. 20(c).

A better approach is for OS to initiate negotiations with TS. Unlike Scenario 1, where both parties negotiated the collision avoidance decision of TS, this scenario simulates negotiations regarding the decisions of OS.



a) Initial encounter situation (b) CA manoeuvre 1 (b) CA manoeuvre 2

Fig. 20 Initial encounter situation of scenario 3

Table 9 Information about the initial encounter situation

Ship	Position	Heading (degree)	Speed (knot)	Distance (n mile)	True Bearing (degree)
OS(AS)	(16°5′24″, 128°51′3″)	020	15	/	/
TS(CS)	(16°13′12″, 128°54′36″)	200	15	7.98	22.33

Based on previous relevant research and modifications, in this scenario, the OS has estimated the course changes and probabilities for the TS as shown in Table 10, and the estimates of the conditional probability of the TS's decision under the assumption of the OS are shown in Table 11.

Table 10 Estimation of the reserve value of TS by OS of Scenario 3

Reserve Value	r_1	r_2	r_3	r_4	r_5	r_6
Steering angle r_i	0	10	20	30	40	50
Probability $p(r_i)$	0.10	0.20	0.30	0.20	0.10	0.10

Table 11 The conditional probability of TS's decision under the assumption of OS of Scenario 3

Assumption		Probability								
		q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	q_9
		0	5	10	15	20	30	40	50	60
r_1	0	0.10	0.65	0.25	0	0	0	0	0	0
r_2	10	0.10	0.75	0.10	0.05	0	0	0	0	0
r_3	20	0.10	0.10	0.15	0.55	0.10	0	0	0	0
r_4	30	0.05	0.05	0.10	0.30	0.40	0.05	0.05	0	0
r_5	40	0.05	0.05	0.10	0.10	0.25	0.30	0.10	0.05	0
r_6	50	0	0.05	0.05	0.05	0.10	0.25	0.40	0.05	0.05

Calculations reveal that, prior to negotiation, the OS estimates the reserve value of the TS based on prior knowledge is $RV_{TS0} = 23$. During negotiation, OS plans to turn to starboard by 26° and communicates this decision to TS, while expecting TS to also turn to starboard. However, TS informs OS during negotiation that she will not take starboard action and will instead maintain course and speed, expecting OS to turn to starboard by 40°. Subsequently, both ships negotiate the decision of OS. Based on the prior probability estimates and the proposal from the TS, the OS revises the estimate of the retained value of the TS, and the estimation of the reserve value of TS has been updated as $RV_{TS} = 17.3$, the utility function of TS estimated by OS can be expressed as $U_{TS_{CS}} = 1 - 0.0231x$.

As we obtain $Risk_{OS} < Risk_{TS}$, therefore, OS makes concessions. According to the previously defined rules on concession amplitude, OS updates the decision to 31°. OS then notifies TS of the updated decision, and once TS agrees, the negotiation on collision avoidance actions concludes.

The main content of the negotiation is detailed in Appendix C. Initially, OS sends a message to verify the current encounter situation with TS and suggests a course of action. However, TS declines to undertake collision avoidance maneuvers, rejects OS's proposal, and unexpectedly advises OS to increase the steering angle. Upon receiving this suggestion, OS decides to concede through calculation and increases the steering angle. Ultimately, OS executes the maneuver alone and notifies TS, concluding the negotiation.

Fig. 21 illustrates the trajectories when OS adopts Decision 1 (26° starboard turn), Decision 2 (40° starboard turn), and Decision 3 (31° starboard turn). Fig. 22 shows the corresponding variations of DCPA for these three decisions. The values and variations of DCPA confirm the rationality of the three decisions. With the implementation of negotiation methods, OS initially anticipated that TS would also execute a starboard maneuver under COLREGs. Instead, TS not only rejected OS's suggestion but also provided maneuvering advice for OS. Upon evaluating the situation, OS determined that a slight concession by increasing the turning angle was appropriate.

The results indicate that the outcome of the negotiation lies between the proposals of OS and TS, thereby enhancing safety compared with OS's initial decision. This cooperation with TS during negotiation enables OS to fulfil its give-way obligations without engaging in unnecessary maneuvers as suggested unilaterally by TS.

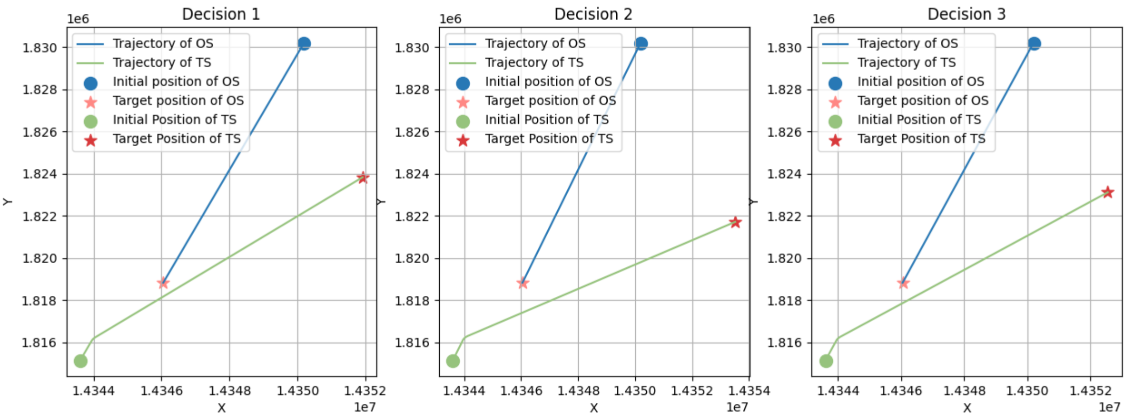


Fig. 21 Negotiated collision avoidance trajectory under the decision proposed by OS

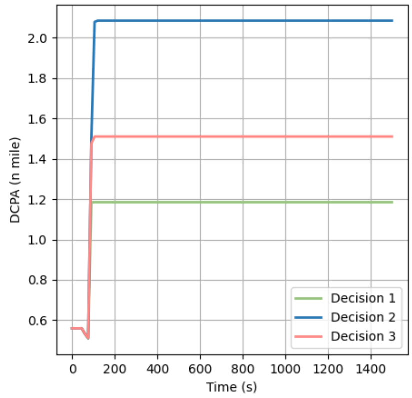


Fig. 22 DCPA variations under the decision proposed by TS

4. Conclusion and discussion

This paper presented a negotiation method for collaborative collision avoidance between autonomous and conventional ships in mixed navigation scenarios. It develops a negotiation framework integrating the Zeuthen strategy and Bayesian learning. This method addresses the problem of asymmetric information exchange and differing decision-making logic between autonomous and conventional ships in uncoordinated collision avoidance scenarios. It breaks through the limitations of the traditional "unilateral collision avoidance" approach and provides a solution for resolving decision-making conflicts between the two ship types. Validation across various scenarios demonstrates that this method enables ships to negotiate effectively, respond to uncoordinated collision avoidance actions, and achieve mutually acceptable decisions. By elevating autonomous ships' decision-making beyond traditional autonomous algorithms, this research advances the development of autonomous navigation and enhances maritime safety.

The model incorporates an organizational model that transforms negotiation into a mathematically describable process, and a procedural model that provides a framework for effective communication. The Zeuthen strategy enables negotiators to make concessions based on anticipated gains and risk tolerance. Autonomous ships leverage Bayesian learning to improve their estimation of conventional ships' utility functions, thereby enhancing negotiation capability.

However, to ensure effectiveness, this study did not consider scenarios involving multiple ships. Although two-ship collision avoidance is a common occurrence, multi-ship negotiation must be investigated, particularly in congested waterways. Future research will aim to address this limitation by establishing a comprehensive scenario library and database based on expert knowledge and statistical data to support negotiation methods, mining and defining uncoordinated collision scenarios to facilitate negotiation, and developing more suitable human-machine interaction systems to further improve safety in hybrid navigation environments. In addition, robust cybersecurity measures are essential to protect maritime autonomous systems from evolving cyber threats [36][38]. Ensuring the security of communication networks during negotiation is a critical consideration.

While the proposed negotiation-based method demonstrates effectiveness in controlled simulations, several practical factors must be acknowledged. First, ship heterogeneity—including variations in size, maneuverability, and equipment—may influence negotiation dynamics and the applicability of utility functions. Second, human factors remain critical: conventional ships are operated by officers whose risk preferences, situational awareness, and compliance with COLREGs vary, potentially affecting negotiation reliability. Third, environmental influences such as wind, current, and restricted visibility may alter encounter dynamics and the feasibility of communication channels. Although these aspects were not explicitly modeled, they represent essential directions for future work. Incorporating vessel diversity, human-in-the-loop testing, and environmental robustness analysis will enhance the practical applicability of the proposed method in real maritime operations.

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APPENDIX A

$$p(r_1|q_5) = 0 \tag{A.1}$$

$$p(r_2|q_5) = \frac{p(r_2) * p(q_5|r_2)}{\sum_{i=1}^{7} p(q_5|r_i)p(r_i)} \approx 0.02584 \tag{A.2}$$

$$p(r_3|q_5) = \frac{p(r_3) * p(q_5|r_3)}{\sum_{i=1}^{7} p(q_5|r_i)p(r_i)} \approx 0.090439 \tag{A.3}$$

$$p(r_4|q_5) = \frac{p(r_4) * p(q_5|r_4)}{\sum_{i=1}^{7} p(q_5|r_i)p(r_i)} \approx 0.697674 \tag{A.4}$$

$$p(r_5|q_5) = \frac{p(r_5) * p(q_5|r_5)}{\sum_{i=1}^{7} p(q_5|r_i)p(r_i)} \approx 0.155039 \tag{A.5}$$

$$p(r_6|q_5) = \frac{p(r_6) * p(q_5|r_6)}{\sum_{i=1}^{7} p(q_5|r_i)p(r_i)} \approx 0.02584 \tag{A.6}$$

$$p(r_7|q_5) = \frac{p(r_7) * p(q_5|r_7)}{\sum_{i=1}^{7} p(q_5|r_i)p(r_i)} \approx 0.005168 \tag{A.7}$$

$$RV_{TS1} = \sum r_i \times p(r_i) \approx 40.8 \tag{A.8}$$

APPENDIX B

$$p(r_1|q = 33) = 0 \tag{B.1}$$

$$p(r_2|q = 33) = \frac{p(r_2) * p(q = 33|r_2)}{\sum_{i=1}^{7} p(q = 33|r_i)p(r_i)} \approx 0.020546 \tag{B.2}$$

$$p(r_3|q = 33) = \frac{p(r_3) * p(q = 33|r_3)}{\sum_{i=1}^{7} p(q = 33|r_i)p(r_i)} = 0.17464 \tag{B.3}$$

$$p(r_4|q = 33) = \frac{p(r_4) * p(q = 33|r_4)}{\sum_{i=1}^{7} p(q = 33|r_i)p(r_i)} \approx 0.545935 \tag{B.4}$$

$$p(r_5|q=33)=\frac{p(r_5)*p(q=33|r_5)}{\sum_{i=1}^{7}p(q=33|r_i)p(r_i)}\approx 0.202524 \tag{B.5}$$

$$p(r_6|q=33)=\frac{p(r_6)*p(q=33|r_6)}{\sum_{i=1}^{7}p(q=33|r_i)p(r_i)}\approx 0.046962 \tag{B.6}$$

$$p(r_7|q=33)=\frac{p(r_7)*p(q=33|r_7)}{\sum_{i=1}^{7}p(q=33|r_i)p(r_i)}\approx 0.009392 \tag{B.7}$$

$$RV_{TS2}=\sum r_i\times p(r_i)\approx 41.1 \tag{B.8}$$

$$U_{TS_{CS}1}=1-(1-U_{X_{RV}})*\frac{x-X_{Optimal}}{RV_{TS2}-X_{Optimal}}=2.35-0.044x \tag{B.9}$$

$$MRT_{OS}^2=\frac{U_{aa}^2-U_{ac}^2}{U_{aa}^2-U(a)}=0.2310 \tag{B.10}$$

$$MRT_{TS}^2=\frac{U_{cc}^2-U_{ca}^2}{U_{cc}^2-U(c)}=0.5752 \tag{B.11}$$

APPENDIX C

$$Verify: NAME(TS)SITUATION(HEAD-ON)RESPONSIBILITY(Give-way) \tag{C.1}$$

$$Inform: NAME(OS)MANOEUVRE(TURNSTARBOARD)STEERINGANGLE(26) \tag{C.2}$$

$$Request: NAME(TS)MANOEUVRE(TURNSTARBOARD) \tag{C.3}$$

$$Disagree: NAME(TS)MANOEUVRE(KEEP\ COURSE) \tag{C.4}$$

$$Advise: NAME(OS)MANOEUVRE(TURNSTARBOARD)STEERINGANGLE(40) \tag{C.5}$$

$$Inform: NAME(OS)MANOEUVRE(TURNSTARBOARD)STEERINGANGLE(31) \tag{C.6}$$

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