Exchange of messages to prevent ship collisions

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Abstract. This study proposes a method to find the optimal number of information exchange messages of the Distributed Local Search (DLSA) algorithm for collision avoidance between ships. In this study, the cost of determining the moving position of a ship is defined as the sum of the collision risk between ships and the cost to reach the destination. This total is used as the maximum cost to define the upper limit of message exchanges. In the experiment, the number of ships varied from 2 to 20. Changes in the maximum cost and the number of message exchanges were recorded, and the number of message exchanges was limited to 5 in all cases. The experimental results using AIS data showed that the upper limit number of message exchanges of 25 and 50 successfully guaranteed collision avoidance for 5 and 10 ships, respectively.

Keywords: Distributed Local Search Algorithm, Maximum Cost, Upper Bound Number of Messages.

1 Introduction

Global crises persist, including inflation stemming from the Ukraine-Russia war, food shortages, high transportation costs, and supply chain disruptions. Nonetheless, over 80% of global trade occurs via sea routes [1]. As depicted in Figure 1, the number of major ships continues to rise, with bulk carriers showing the most rapid increase, while oil tankers have decreased from 30% to 29%, and general cargo ships from 5% to 4%.

Despite advancements in AI technology and ship equipment, maritime accidents remain prevalent, often resulting in greater damage compared to other types of accidents. Notable incidents include the 2011 collision between a container ship and a bulk carrier [2], a ship colliding with a bridge in 2019 [3], and a cruise ship sinking after colliding with another cruise ship in Hungary in 2019 [4], resulting in numerous casualties.

In Korea alone, 2,863 maritime accidents occurred in 2022, with 244 involving ship collisions, ranking second after engine failures (Fig. 2). Maritime Autonomous Surface Ships (MASS) are being developed to mitigate collision accidents, driven further by global supply chain vulnerabilities exacerbated by labor shortages and COVID-19 lockdowns [5]. The market for MASS is expected to grow significantly.

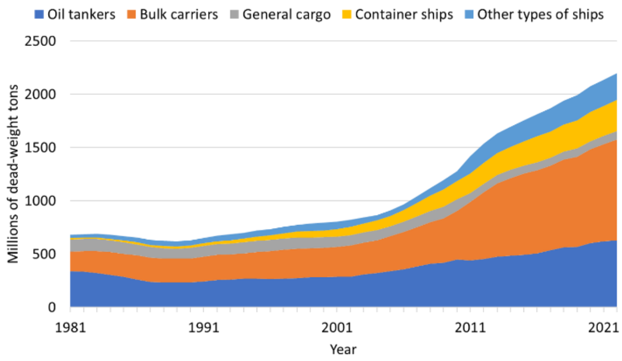
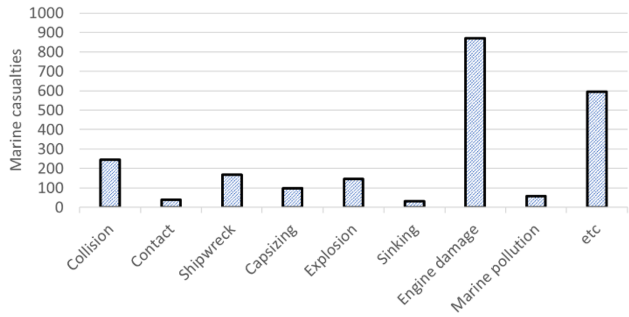


Fig. 1. Change of World fleets

Fig. 2. Accident Event Type



Most research on ship collision avoidance focuses on one-to-many scenarios, where experiments assume surrounding ships do not evade collision, leaving avoidance maneuvers solely to the main ship. However, ship avoidance maneuvers influence others, prompting affected ships to adjust their own courses. Hence, information exchange between ships to predict movements is crucial.

A distributed algorithm based on information exchange among ships was proposed [6] to optimize avoidance paths when multiple ships encounter each other. This study proposes an optimal message exchange method based on the Distributed Local Search Algorithm (DLSA) to enhance this approach. Chapter 2 discusses prior studies on ship collision avoidance with information exchange. Chapter 3 introduces the DLSA algorithm, emphasizing its ease of implementation, route backtracking capability, and bidirectional message exchange. Chapter 4 presents experimental findings on optimizing message exchanges using DLSA.

2 Previous studies

Ships cannot halt abruptly due to their significant inertia, necessitating proactive search for safe escape routes when encountering multiple ships, a task complicated by high-speed navigation. Numerous methods have been proposed to prevent ship collision accidents across these scenarios.

Initially, the Mathematic Model Groups (MMG) model was introduced for predicting steering performance [7, 8, 9, 10]. The Collision Risk Index (CRI) method, calculated from weights multiplied by DCPA and TCPA, was also proposed [11, 12]. Another approach, the Ship Domain method, presumed collision if an approaching ship entered the planned route of the main ship [13, 14].

Further innovations included the Virtual Vector Field method employing Artificial Potential Fields to guide ships safely to destinations by repelling obstacles and attracting towards goals [15, 16], as well as the Limited Cycle Method (LCM) [17, 18, 19]. Recent efforts involve research using reinforcement learning and artificial intelligence for collision avoidance [20, 21, 22].

Despite these advances, accurately predicting target ship movements remains challenging, highlighting the need for information exchange algorithms. Table 1 outlines various information exchange-based ship collision avoidance algorithms. These include multi-agent simulations with flexible agent characteristics and variable topologies [23], predictive models for uncooperative ship movements based on AIS data, and probabilistic trajectory optimization methods [24]. Methods comparing message exchanges between ships to optimize information flow have also been proposed [25]. To mitigate local minima in distributed algorithms, tabu search algorithms have been applied [26], alongside real-time distributed algorithms incorporating COLREGs for collision avoidance [27]. Other approaches like MTCAS utilize ship dynamics and environmental data [28].

In this study, we propose an optimal message search using the Distributed Local Search Algorithm (DLSA) for ship collision avoidance based on information exchange. This method aims to enhance the efficiency and reliability of ship avoidance maneuvers in complex maritime environments.

3 DLSA Architecture

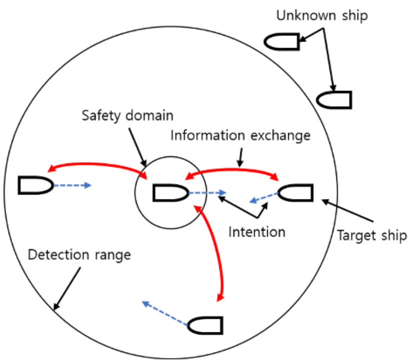
DLSA operates synchronously, ensuring all ships exchange messages simultaneously. Synchronization ensures accurate transmission and reception timing between transmitters and receivers. In DLSA, each ship is equipped with a Detection Range, representing its maximum detectable distance for exchanging information with neighboring ships, as illustrated in Fig. 3. Within this range, ships share information crucial for calculating optimal paths within a limited timeframe. The algorithm continuously seeks the path with the lowest cost among those evaluated, progressing to the next location until the destination is reached.

Table 1. Existing research based on information exchange between ships

Ref.	Method	Central/ Decentral	Two/Multi-ple ship	Synchro/Asyn-chro	COLREGs considered
[23]	Negotiation-based multi-agent	Decentral	Multi	Synchro	V
[24]	planning	Decentral	Multi	Asynchro	V
[25]	Nash bargaining	Decentral	Multi	Synchro	V
[26]	DSSA	Decentral	Multi	Synchro	V
[27]	DTSA	Decentral	Multi		V
[28]	Anti-collision deci-sion making	Decentral	Two		V
[31]	MTCAS	Decentral	Multi	Synchro	-
[29]	NMPC	Decentral	Multi		-
[9]	CMVs, CWIS	Decentral	Multi	Synchro	-
[30]	distributed coordi-nation mechanism	Decentral	Multi	ASynchro	-
[6]	DLSA	Decentral	Multi	Synchro	V

V: Applicable, -: Not Applicable

Fig. 3. Terminology of DLSA



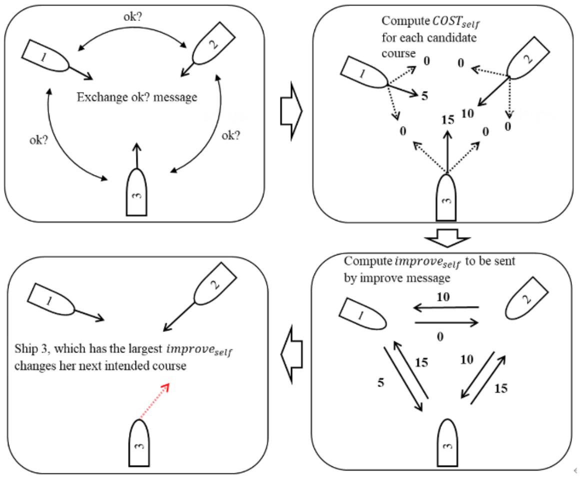


Fig. 4. Procedure of DLSA

DLSA functions as a message-based collision avoidance algorithm [6]. Ships exchange two types of messages: "Ok?" messages containing location information, and "Improvement" messages indicating the additional cost of selecting a new avoidance path compared to the current one.

Each ship also defines a Safety Domain. If an target ship breaches this domain, a collision is deemed imminent. Within the Detection Range, neighboring ships exchange information, while ships beyond this range are considered Unknown and cannot exchange data. Parameters like Detection Range, Safety Domain, and Intention are adjustable. For instance, setting the Detection Range to 12 nautical miles enables information exchange with neighboring ships within that distance. A Safety Domain set at 1 nautical mile signifies potential collision if an target ship approaches within this range. Reducing Safety Domain to 0.5 nautical miles can decrease avoidance maneuvers or course change angles.

Figure 4 illustrates the message exchange protocol of DLSA. Each ship exchanges Ok? messages with neighboring ships within its Detection Range, sharing their next intended locations. Subsequently, each ship calculates the avoidance path cost based on the next location of the target ship and transmits the optimal improvement message aimed at minimizing this cost. The ship receiving the most favorable improvement message among its neighbors selects its next avoidance action. This iterative process continues until the destination is safely reached.

4 Experiments

4.1 Determine the upper limit of number of messages

The cost required for a ship to determine its next position is as shown in Equation (1). $CR_{self}(course, j)$ represents the risk of each course for the target ship j. $\theta_{destination}$ represents the bearing to the destination, and $\theta_{self}(course)$ represents the bearing of each course.

$$Cost_{self}(course) \equiv \alpha \sum CR_{self}(course, j) + \frac{|\theta_{destination} - \theta_{self}(course)|}{180°} \quad (1)$$

Here, α represents the weight and $self$ represents each ship. The CR_{self} of the first half added to the cost is calculated as follows:

$$CR_{self}(course, k) \equiv \begin{cases} \frac{TimeWindow}{TCPA_{self}(course,k)}, if\ self\ will\ collide\ with\ ship\ k \\ 0, other \end{cases} \quad (2)$$

TimeWindow means the time for the ship to recognize the collision and has a fixed value. TCPA means the remaining time until the closest contact. The sum of all messages generated between ships is as shown in Equation (3).

$$Total\ message \equiv \sum_i \sum_r ShipMessage_{ir} \quad (3)$$

i represents a ship, and r represents a message generated from each ship. The total number of messages generated from a ship is set to not exceed the upper limit message as in Equation (4).

$$\sum_r message_r \leq UpperLimitOfMessage \quad (4)$$

The average sailing distance was calculated by dividing the sailing distance of all ships by the number of ships, as in Equation (5).

$$AverageSailingDistance \equiv \frac{1}{TotalShip} \sum_i \sum_{t=2} |position_i^t - position_i^{t-1}| \quad (5)$$

i indicates the ship's spinal column, and t indicates the ship's position.

As shown in Fig. 5, the maximum cost of collision avoidance between two ships is determined, and the message that occurred at this time is determined as the upper limit message exchange number. In other words, the number of message exchanges in the most dangerous situation is determined as the upper limit message exchange number.

As shown in Fig. 6, the maximum cost for a collision with an target ship in a 1:1 situation can be calculated as follows. In the situation where *TimeWindow* is 15 min and *TCPA* is 3 min, the cost for one target ship for the current course $000°$ is

$CR_{self}(000°, TargetShip1) = \frac{15}{3} = 5$, and since the current bearing and the bearing for the destination are the same, $|0° - 0°|/180° = 0$. Therefore, $CR_{self}(000°) = 5 + 0 = 5$ becomes the maximum cost.

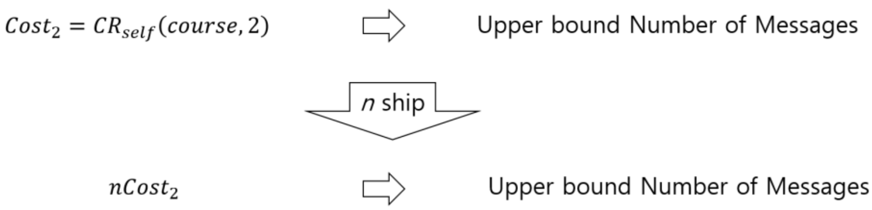


Fig. 5. Determining the upper limit of the number of message exchanges of *n* ships

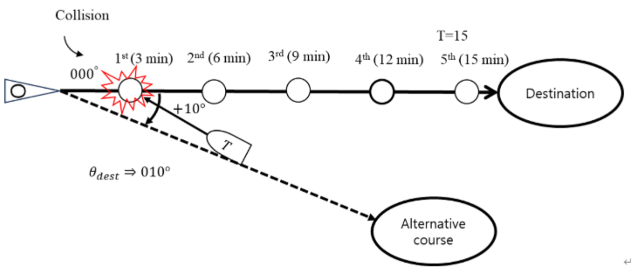
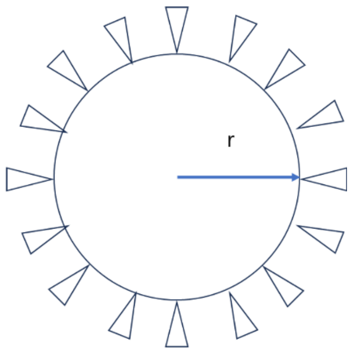


Fig. 6. Example of How to compute Cost

Fig. 7. Circle-based Ship Collision Avoidance Model

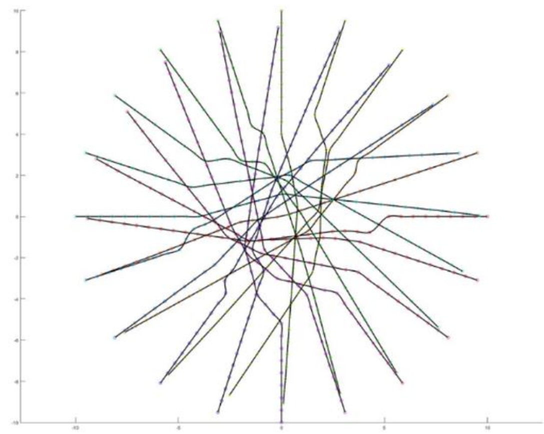


The maximum cost per target ship is 5, and the maximum cost increases linearly as the number of ships increases. In other words, when there are 2 target ships, the maximum cost is calculated as maximum cost 5 X target ship 2 = 10. As shown in Table 2, the cost increases linearly as the number of ships increases. This is the value that serves as the criterion for the upper limit of message exchanges, and a circular-based collision avoidance model was used to obtain the value that serves as the criterion for the upper limit of message exchanges.

Table 2.

Number of ship	Cost
2	10
3	15
…	…
19	95
20	100

Fig. 8. Collision avoidance simulation of 20 ships



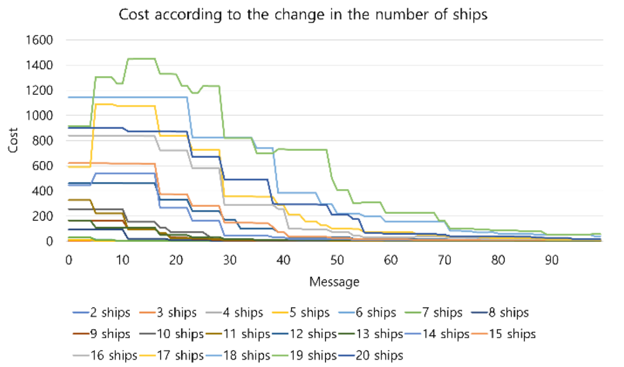


Fig. 9. Cost according to the Change in the number of ships

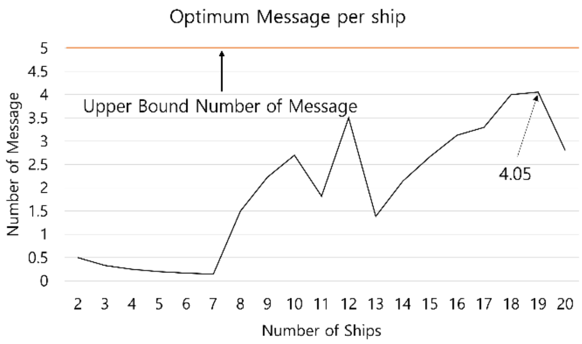


Fig. 10. Optimum Upper Bound Number of Messages

4.2 Circular-based ship collision avoidance experiment

The number of message exchanges per experiment ranged from 1 to 100, and a total of 1,900 experiments were conducted with 2 to 20 ships. A circle-based ship collision experiment was conducted as shown in Figure 7. The reasons for conducting the experiment using a circle are as follows:

● The relative position conditions of all ships are the same.

● By having all ships meet at the center of the circle, collision avoidance can be tested in the most complex situation.

Figure 8 illustrates a circle-based collision avoidance simulation involving 20 ships. All ships set their destination at the farthest opposite end of the circle and successfully avoided collisions. As a result, all ships arrived at their destinations safely.

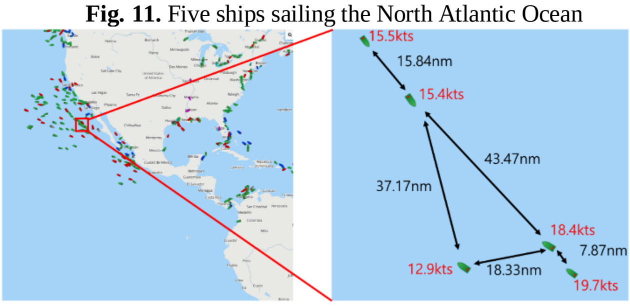
Figure 9 shows the cost when the upper limit of message exchanges varies with the number of ships. For instance, as the upper limit of message exchanges for 20 ships increases, the cost decreases, with 56 messages recorded at a maximum cost of 100 (maximum cost 5 X number of ships 20). Calculated this way, the number of messages per ship is depicted in Figure 10. This indicates that when exchanging messages between multiple ships, fewer than 5 exchanges are required to determine the next location for each ship.

As shown in Figure 10, the upper limit number of message exchanges was determined to be 5. Subsequently, using the AIS data of an actual ship, the upper limit number of messages was limited to 5, and the experiment was conducted.

Table 3. Ship's dynamic information and parameter setting for 5 ships

Ship	Lat(N)	Long(W)	Speed(knots)	Heading(˚)	Safety Domain	Detection Range(nm)
1	21.04215	107.58977	15.5	144	3	12
2	20.83193	107.41500	15.4	145	3	12
3	20.23619	107.21483	12.9	304	3	12
4	20.31226	106.88966	18.4	301	3	12
5	20.21492	106.80164	19.7	306	3	12

Fig. 11. Five ships sailing the North Atlantic Ocean



4.3 Multi-vessel avoidance experiment using AIS data

Using AIS data from 5 vessels

Fig. 11 shows a ship sailing in the North Atlantic. A total of 5 ships encounters each other, and the situation is a mix of head-on, crossing, and overtaking. Table 2 shows the dynamic information of the 5 ships, as well as the Safety domain and Detection Range settings.

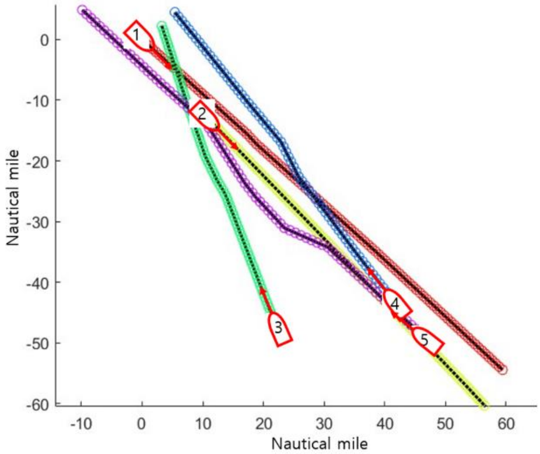


Fig. 12. Result of collision avoidance of 5 ships

Fig. 13. Ships navigating waters near Morocco

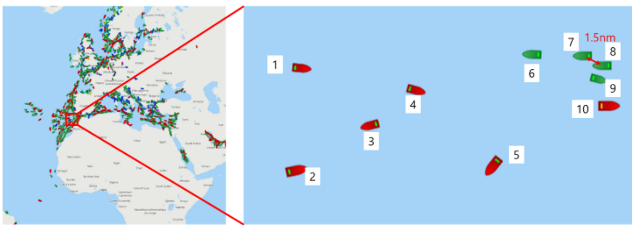
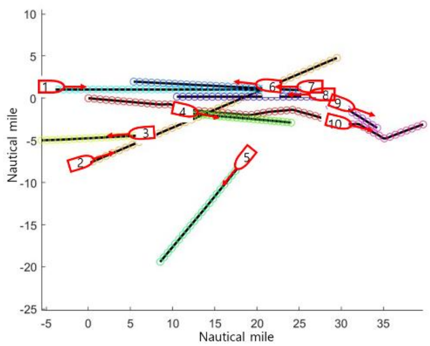


Fig. 14. Result of collision avoidance of 10 ships



The experimental results are shown in Fig. 12, and the 5 ships arrived at the destination after avoiding collisions. The average navigation distance and total number of message exchanges at this time are shown in Table 4.

Table 4. Average sailing distance and total number of message exchanges when upper bound number of messages are 5 for 5 ships

Upper Bound Number of Message	Average Sailing Distance	Total Message
5	342.0600	632

Using AIS data from 10 vessels

As shown in Fig. 13, an experiment was conducted using AIS data of ships sailing in the waters near Morocco. The colors are displayed differently depending on the type of ship. Red indicates a tanker, and blue indicates a general cargo ship. AIS information of a total of 10 ships was confirmed. Table 5 shows the dynamic information and Safety domain and Detection Range settings of the 10 ships.

The experimental results are as shown in Fig. 14, and 10 ships avoided collisions and arrived at the destination. The average navigation distance and total number of message exchanges at this time are as shown in Table 6.

Table 5. Ship's dynamic information and parameter setting for 10 ships

Ship	Lat(N)	Long(W)	Speed(knots)	Heading(˚)	Safety Domain	Detection Range(nm)
1	6.79088	35.9447	13.0	096	1	12
2	6.79525	35.8138	9.2	078	1	12
3	6.67797	35.87132	12.4	255	1	12
4	6.60588	35.91557	12.7	105	1	12
5	6.48565	35.81897	12.2	218	1	12
6	6.43214	35.96169	12.4	270	1	12
7	6.35172	35.95981	10.0	269	1	12
8	6.32433	35.94739	15.5	270	1	12
9	6.31392	35.92880	10.0	103	1	12
10	6.30351	35.89615	12.8	090	1	12

Table 6. Average sailing distance and total number of message exchanges when upper bound number of messages are 5 for 10 ships

Upper Bound Number of Message	Average Sailing Distance	Total Message
5	184.3500	2132

5 Conclusion

In this study, we propose optimizing the number of message exchanges between ships using the Distributed Area Search Algorithm. Previous research has predominantly focused on scenarios involving one-to-many ships, with limited mention of the specific number of message exchanges during ship-to-ship information exchange. The study can be summarized as follows:

- The experiments utilized a circle-based collision model. This model ensures consistent relative ship positions, directing all ships towards the circle's center and opposite destinations, thus simulating complex scenarios effectively.
- We assumed a linear increase in costs with the number of ships, based on maximum collision avoidance costs between two ships under the most hazardous conditions.
- Through simulations involving 2 to 20 ships, we determined that the maximum number of message exchanges per ship is 5.
- Experiments were conducted using AIS data from 5 and 10 actual ships. By limiting the maximum message exchanges to 5, we observed that all ships safely reached their destinations.
- While this study employed a circle-based collision model, future research should explore more diverse collision models. Additionally, varying speeds and Safety Domain settings should be considered to reflect the diverse characteristics of real-world ships.

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