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Optimal Search for Underwater Targets for Ships Equipped with Hull Mounted Sonar Using Genetic Algorithm

Y. S. Hwang[1,2] and Y. H. Ha[1*]

[1] *Korea National Defense University, Nonsan, Republic of Korea*
[2] *Sejong University, Seoul, Republic of Korea*

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Abstract:

When a surface ship utilizes a hull-mounted sonar (HMS) to search for a target located in the water at sea, the maneuver path of the surface ship depends on the maximum detection range of the sonar. Because sonar utilizes sound waves, it is significantly influenced by the marine environment and the detection probability depends on the location and sound wave incident angle of the target. This study aims to calculate the detection probability by applying the actual marine environment, and proposes an optimal search path calculation method that maximizes the detection probability based on a genetic algorithm. The proposed optimal search path calculation method was proven to be effective via simulations in determining the optimal search.

Keywords:

cumulative detection probability, genetic algorithm, optimal searching, underwater target detection

1 Introduction

When a surface ship equipped with an HMS searches for an underwater target at sea, it maneuvers at a limited speed considering the noise of the ship. The limitation in speed extends the search time, and the uncertainty of the target position increases as the search time increases. Therefore, it is necessary to search for the target within the shortest time possible. To search for a target in the shortest time, it is necessary to fully increase the detection probability. It is possible to calculate the detection probability of a target ac-

* *Corresponding author: Department of Defense Science, Korea National Defense University, 33021 1040, Hwangsanbul-ro, Yangchon-myeon, Nonsan-si, Chungcheongnam-do, Republic of Korea. Phone: +820418 31 53 25, E-mail: yonghoonha@mnd.go.kr. ORCID 0000-0002-2516-9510.*

cording to the expected location (depth and distance) of the target through the performance of the sonar mounted on the surface ship, the sea condition, and the target strength. In order to detect a maneuvering target, the surface ship moves to the position with the highest probability of detection and attempts to detect it (sonic transmission). If the surface vessel continuously moves to the position with the highest detection probability and attempts to detect it, the optimal underwater target detection path can be determined for the maneuvering target based on the movement path of the surface vessel.

Studies related to underwater target search include the study on the GRASP algorithm proposed by DelBalzo and Hemsteter [1], as well as the study dealing with the optimal acoustic search path planning in the discrete path system by Cho et al. [2]. Another study concerning the optimal search algorithm considering the ship characteristics and reflecting the marine environment was presented by Kim et al. [3]. In this study we attempt to further develop previous studies to enable the search of moving targets by reflecting the actual marine environment in a continuous path.

Search methods commonly utilized to search for underwater targets at sea include the exhaustive (Ladder Search, Spiral In & Out, etc.) and random searches. As the exhaustive search takes a longer search time, and the random search may involve a different search method depending on the searcher's propensity, it is necessary to develop an optimal underwater target search algorithm.

This study proposes an optimal underwater target search algorithm based on a genetic algorithm. Each gene represents the turning angle of the searcher, and the optimal solution can be reached by the generations. The performance of the developed program has been verified in comparison with that of the random search, by simulation.

This study is different from previous studies in that it presents an algorithm to find the optimal maneuvering path to detect a maneuvering target considering the target strength by implementing a 3-D search space to which the actual ocean environment is applied.

2 Genetic Algorithm

Genetic Algorithm (GA) mimics the mechanism of inheritance and evolution of living things that addresses optimization challenges utilizing the evolutionary principles of the natural world [3-5], where it randomly creates several solutions to given challenges and determines the best solution among them by applying the simplified process of natural selection [6]. GA is widely utilized in search optimization challenges as it determines the optimal value in a short time, among numerous solutions existing in a complex and wide search space using the principles of evolution and selection. In GA, the minimum unit is a gene which has been set as the turning angle in this study. Genes gather to form a single chromosome, and chromosomes gather to form a single generation. The main operations of genetic algorithms include "selection", "crossover", and "mutation". "Selection" is to select the chromosome to be utilized when generating the next generation from the current generation based on "fitness", which tells how suitable the proposed chromosome is to solve the problem. "Crossover" is to create a novel chromosome by combining two chromosomes made up of a group of genes. Using "crossover", a novel chromosome can be created by combining different characteristics from two chromosomes. "Mutation" is to randomly modify a part of the chromosome to prevent falling into the "local optimal solution" by increasing the diversity of chromosomes.

3 Optimal Search Algorithm for Underwater Targets

3.1 Flowchart of the Optimal Search Algorithm for Underwater Targets

Fig. 1 illustrates the flowchart of the optimal search algorithm for underwater targets. Firstly, a three-dimensional marine environment is implemented by utilizing the marine environment information data (sound speed profile; SSP) of the East Sea to define the search space. The acoustic transmission loss (TL) is calculated utilizing the sound velocity distribution data according to the water depth and the acoustic propagation model, Bellhop [7], which is further utilized to calculate the signal excess (SE). In addition, the target detection probability is defined according to the depth and distance from the searcher using the cumulative distribution function (CDF).

To execute the genetic algorithm, a population composed of chromosomes is initialized. The search proceeds by randomly generating the first 100 chromosomes that can perform searching to achieve the maximum value of the fitness. After evaluating the convergence to the solution within the algorithm, a novel generation is created using the "selection", "crossover", and "mutation" operations, and is repeated until the specified number of iterations is reached or cost function less than 20.

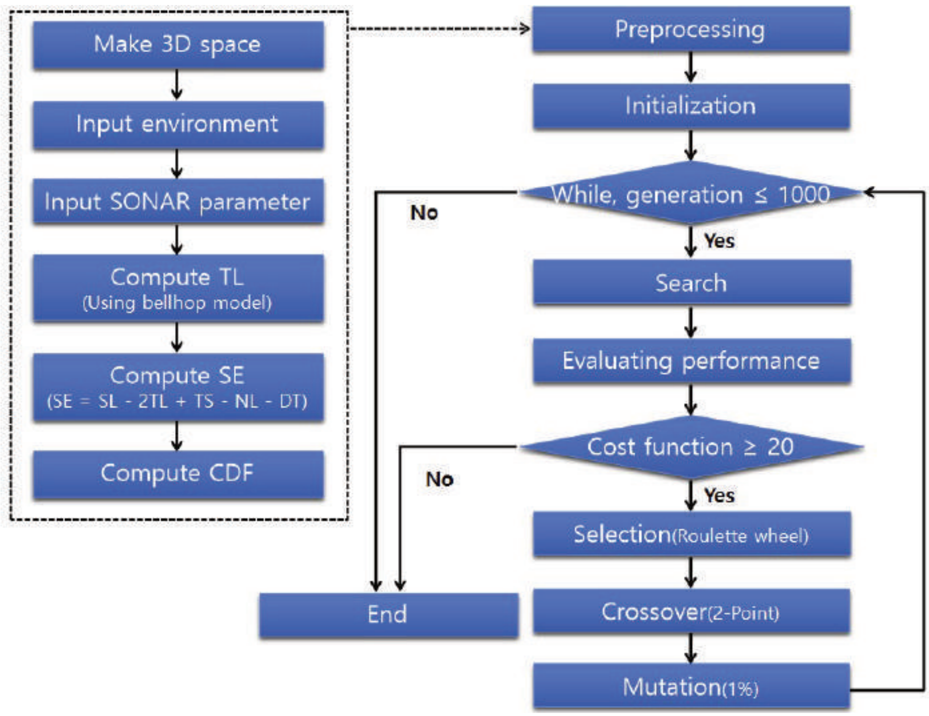

Fig. 1 Underwater Target Optimal Search Algorithm flow chart

3.2 Search Space

This study assumes a continuous path to implement a realistic search. The size of the three- dimensional search space is (20 × 20 × 2) km (depth), and the sound velocity distribution data according to the depth of the East Sea is utilized to implement the acoustic propagation environment. The target is located in the center of the search space, on the water surface, and it starts submerging at 1 m per second, and maintains the depth when positioned at 200 m considering the optimal depth for submarine to operate, called best depth (BD) in the oceanography. The target has been assumed to maneuver in a straight line at a speed of 9 km/h (5 kts) to leave the initial position within the shortest time. Considering the Earth's curvature, the maximum distance a surface ship can detect the periscope of a submarine with R/D is approximately 10 km to 14 km. Therefore, the searcher starts searching at a position of 225° and 10 km from the initial position of the target, and the initial course was set to 045° to enable the searcher maneuver toward the initial position (Datum) of the target.

3.3 Calculate the Fitness

Because this study attempts to utilize the HMS mounted on the surface ship to search for the target in active mode, the SE value, which is an indicator of the detection performance of the sonar, is required. As aforementioned, the acoustic TL is calculated utilizing Bellhop, an acoustic propagation model, for the marine environment information in the East Sea. By substituting it into the sonar equation in Eq. (1), the SE value of the active sonar can be calculated:

$$\mathrm{SE} = \mathrm{SL} - 2\mathrm{TL} + \mathrm{DI} - \mathrm{NL} + \mathrm{TS} - \mathrm{DT} \tag{1}$$

where SL denotes the source level [dB], TL denotes the transmission loss (dB), DI denotes the directivity index [dB], NL denotes the noise level [dB], TS denotes the target strength [dB], and DT denotes the detection threshold [dB].

When SE becomes zero, the detection probability is 50 %, and the maximum detection distance is calculated considering this. The system parameters of the hull-mounted sonar required for the SE calculation can be changed by user and Tab. 1 represents the sonar parameter used for this study.

Tab. 1 Active Sonar Parameter (Specification) used in Eq. (1)

Active Sonar Parameters		**Value**
Frequency		5 kHz
Source Level (SL)		230 dB
Source Depth		20 m
Target Strength (TS)	Bow-stern	10 dB
	Intermediate	15 dB
	Beam	25 dB
Noise Level (NL)		41 dB
Directivity Index (DI)		0 dB
Detection Threshold (DT)		25 dB

Fig. 2 illustrates the sound velocity distribution according to the water depth for TL calculation.

The target strength (TS) depends on the sound wave incident angle on the target. In this study, Bow-stern 10 dB, Intermediate 15 dB, and Beam 25 dB were utilized by citing the well-known “Nominal Value of Target Strength” in reference [8]. Regarding the noise level, the spectrum level of the ambient noise for the average deep sea [8] was cited, and 41 dB was set assuming good sea conditions, with the directivity index (DI) set to 0 dB considering omnidirectional detection. The detection threshold (DT) was assumed to be 25 dB.

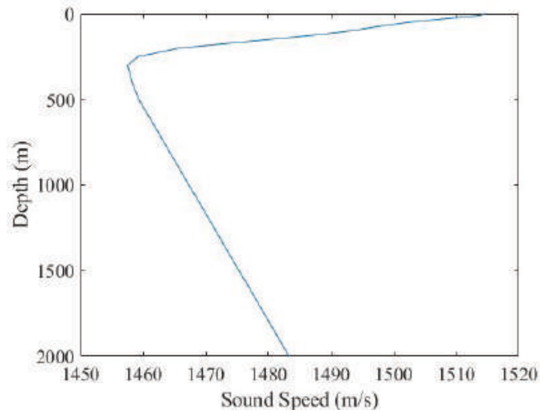

Fig. 2 Sound Speed Profile in East Sea

The SE value can be obtained using Eq. (1) with the sonar system variables, and the SE value of the sonar can be converted into a detection probability (P_{d}) using Eq. (2) which is cumulative distribution function (CDF):

$$P_{\mathrm{d}}(\mathrm{SE}) = \frac{1}{\sqrt{2\pi\sigma}} \int_{-\infty}^{\mathrm{SE}} \exp\left(-\frac{x^2}{2\sigma^2}\right) \mathrm{d}x \qquad (2)$$

where σ denotes the standard deviation for signal excess, which has been assumed as 8 dB to calculate the detection probability in this study.

Fig. 3 illustrates the detection probability according to the distance calculated using the above equation.

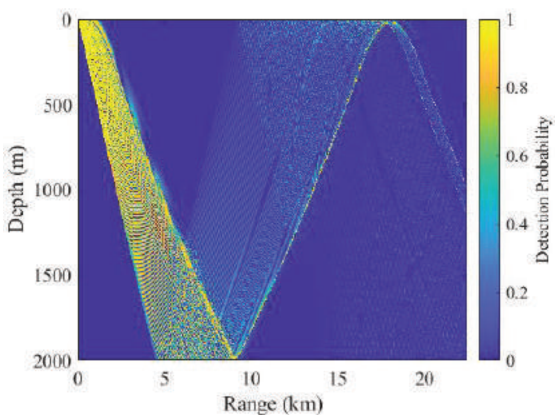

Fig. 3 Target Detection Probability by Range from Searcher
(The detection probability decreases as it moves away from the position of Searcher along the sound wave)

The detection probability is converted to the normalization of the sum of the instantaneous detection probabilities (P_{fd}) using the following equation:

$$P_{\text{fd}} = \frac{1}{N}\sum_{i=1}^{N} P_{\text{d}}\left(i\right) \tag{3}$$

where i denotes the number of acoustic transmissions.

Because the searcher transmits a sound wave once every 180 s, and calculates the detection probability according to the target's location, the number of acoustic transmissions N during the total search time of 7 200 s is 40. The sum of the instantaneous detection probabilities calculated through this (P_{fd}) was utilized as the final detection.

Using Eq. (3), cost function C_{p} could be calculated as follows:

$$C_{\text{p}} = 1 - P_{\text{fd}} \tag{4}$$

where C_{p} represents the cost of the p^{th} chromosome.

Given the above, we can calculate fitness value as follows:

$$F_i = \left[C_{\text{w}} - C_i + \frac{C_{\text{w}} - C_{\text{b}}}{k-1} \right] \times N \tag{5}$$

where F_i represents the fitness of the i^{th} population, C_{w} is the cost of the worst solution, C_{b} is the cost of the best solution, C_i is the cost of the i^{th} solution, k is a constant that determines the likelihood of selection.

3.4 Process of Searching for Underwater Targets

Based on the previously defined chromosomes and fitness calculated, the search is performed while maintaining a total of 100 chromosomes in each generation by utilizing 40 variable genes as one chromosome. Each gene represents a turning angle, and the turning angle comprises 10, 20, and 30 degrees each on the left and right sides. Tab. 2 and Fig. 4 presents the details.

Tab. 2 Searcher's Turning Angle According to Gene

Gene	**Turning Angle**	**Gene**	**Turning Angle**
1	0	5	Turn left 20°
2	Turn right 10°	6	Turn right 30°
3	Turn left 10°	7	Turn left 30°
4	Turn right 20°		

The searcher searches for 7 200 s while maneuvering in a straight line until it is turned by the turning gene of the chromosome. The sound wave is transmitted once every 180 s to prevent the overload of active sonar. To quickly search the search space, the maximum searching speed (maximum speed at which individual surface ships can maneuver without unduly degrading the performance of the sonar) is assumed to be 32 km/h (18 kts) for maneuvering. When the target is detected, the searcher alters the optimum searching speed (the speed at which a surface ship can maintain the maximum search area of the sonar for a period of time under the sea conditions at that time) assumed to be 18 km/h (10 kts) for maneuvering, considering the speed of the target and the noise of the searching ship.

Once a path is completed according to the change of each chromosome and the straight line search, when transmitting sound waves, the searcher performs the search and calculates the detection probability by considering the distance to the target and the sound wave incident angle. After obtaining the final detection probability according to the maneuvering path for each chromosome, outstanding chromosomes are selected as the parent chromosomes using the roulette wheel method. The selected parent chromosomes are crossed by cutting each gene at any two positions by a two-point crossover method. To prevent convergence to the local optimal solution, the mutation was performed with a probability of 1 %, where one gene was selected, and the value of the gene was altered at random.

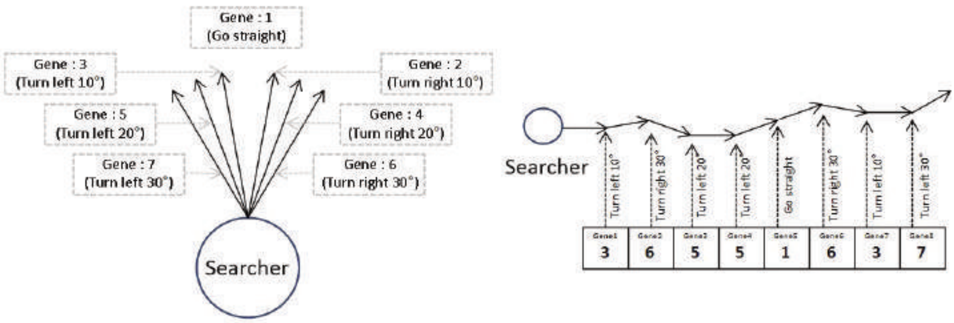

Fig. 4 Example of Searcher Manoeuvers According to Genes

4 Simulation

To evaluate the performance of the algorithm, the final detection value was calculated by increasing the maneuvering range (angle) of the target by units of 5 degrees as shown in Fig. 5, which allowed the prediction of the detection probability during the search, based on the expected location of the target and the search area. Because the algorithm contains random elements, different simulation results are obtained each time. Therefore, because performance evaluation with one simulation is limited, the Monte Carlo method, a probabilistic simulation technique, was applied and the algorithm was repeated 100 times to obtain the statistical results for the final detection probability. Subsequently, the results obtained by the random search and proposed algorithm were compared.

4.1 Results

As Eq. (3), the final detection probability is the normalization of the sum of the instantaneous detection probabilities. Fig. 6 illustrates the results of calculating the final detection probability by expanding the maneuvering range of the target by 5 degrees.
The final detection probability was approximately 0.495 when the target maneuvered solely at 0°. It decreased sharply from 0° to 25°, and then decreased gradually from 25° to 200°. The final detection probability increased from 200° to 275°, and then decreased sharply again after 275°, as the probability of encountering the target head-on occurred when the searcher fixed it to start searching from 225° behind the target. This means that

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the final detection probability increased by approximately 0.125 depending on the initial position of the searcher.

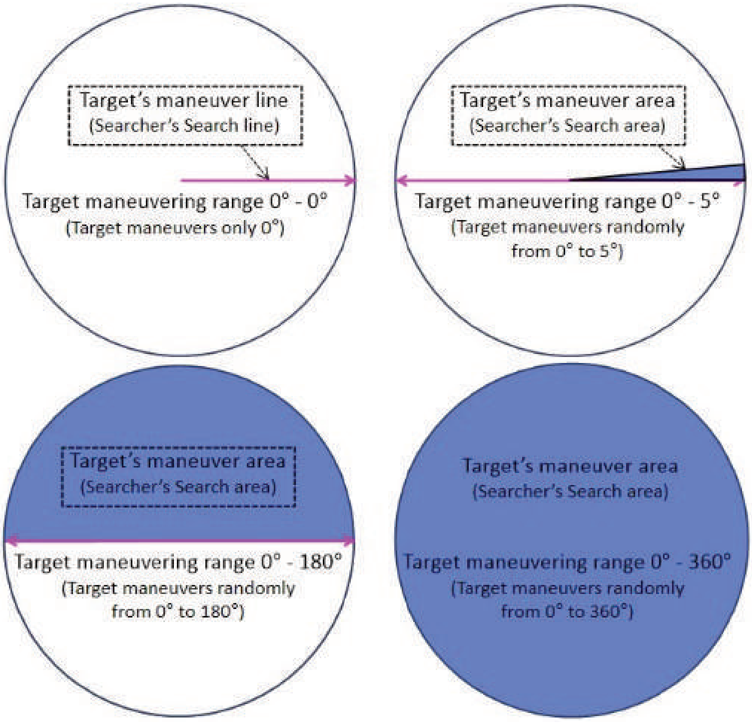


Fig. 5 Example of Increasing Target's Maneuvering Range (Blue shadow part: Target's Maneuver area)

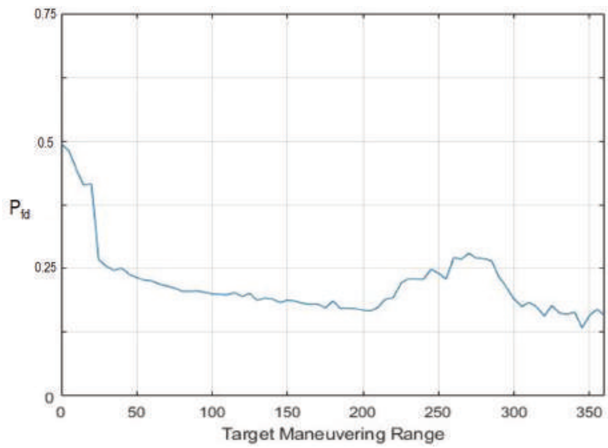


Fig. 6 Final detection probability according to target maneuvering range

To observe how the maneuvering of the searcher altered with the passage of generations, the maneuvering range of the target was fixed at 0° to proceed with the simulation, which revealed that the final detection probability improved with a gradual increase in the number of generations. Fig. 7 illustrates the changes in the final detection probability by generation with the maneuvering range of the target set to 0°.

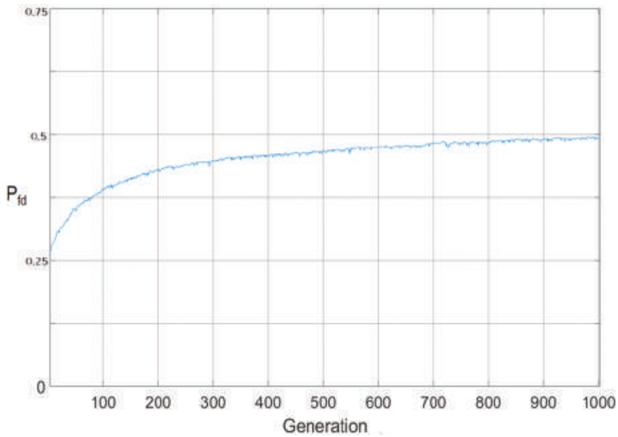
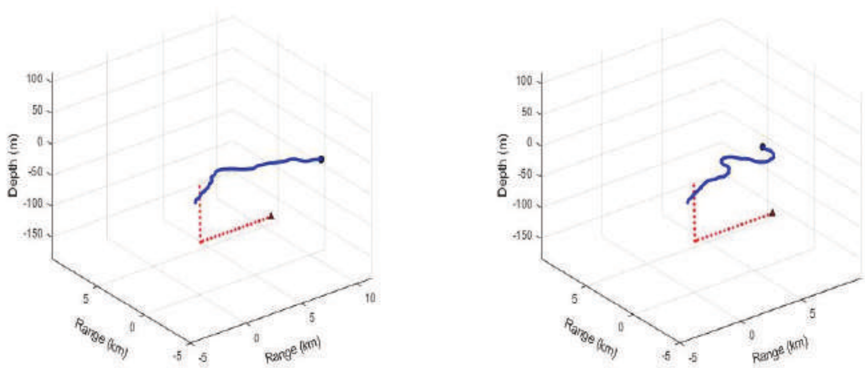


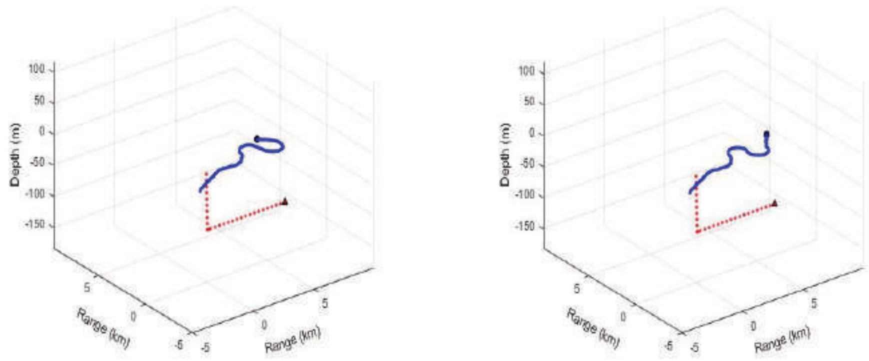
Fig. 7 Final detection probability by generation

Regarding the change in the final detection probability by generation, the final detection probability increased rapidly from the first generation to the 200th generation, increased gradually from the 200th generation to the 900th generation, and barely increased from 0.49 after the 900th generation. There are three factors that contribute to the appearing tremors, rather than forming a smooth curve while the final detection probability increases in general: first, the random selection of parent chromosomes by the roulette wheel method; second, the mutation occurring with a 1 % probability to prevent convergence to the local optimal solution; and third, the utilization of real marine environment data, which could result in a lower final detection rate, despite approaching the target successfully.

Fig. 8 illustrates the changes in the maneuvering path of the searcher when the maneuvering range of the target is 0-0°. The solid line and circle indicate the movement path and final position of the searcher, respectively, while the dotted line and triangle indicates the movement path and final position of the target, respectively.



10th generation search (P_{fd} = 0.26) *100th generation search* (P_{fd} = 0.51)



250th generation search (P_{fd} = 0.56) *500th generation search* (P_{fd} = 0.61)

Fig. 8 Searcher maneuver for the individual generation (Blue line: Searcher maneuver, Red dotted line: Target maneuver)

4.2 Comparison of Performance Between Optimal Search Algorithms for Underwater Targets

Methods for searching for underwater targets at sea include exhaustive and random searches. While exhaustive search methods include Spiral In & Out and Ladder Search, these methods are not widely utilized in general because of the limitations in searching all search space with a wide furthest-on-circle (FOC) following the delay in time until the searcher reaches the target final position (Datum) and speed limit for the sonic search. Therefore, this study assessed the performance by comparing the performance of the random search and the proposed algorithm.

Random search is a method of randomly searching a search space without a set frame or rule, which obtains different search results each time. Therefore, the random search was also repeated 100 times, and the average value of the results obtained was calculated. Regarding the search space and maneuvering of the searcher, similar conditions were applied for the proposed algorithm and Tab. 3 compares the results obtained by the proposed algorithm with those obtained by the random search. The proposed algorithm demonstrated superior performance compared to the random search, regardless of the maneuvering range of the target.

Tab. 3 Comparison of the algorithm results with random search results after repeating 100 times

Target Heading [°]	Final Detection Probability	
	The Algorithm	Random Search
0-0	0.495	0.032
0-90	0.206	0.032
0-180	0.186	0.032
0-270	0.28	0.032
0-360	0.158	0.032

5 Conclusion

This study presented an optimal search algorithm for underwater targets, enabling the surface ships equipped with HMS detect underwater targets departing from the datum. The sum of the instantaneous detection probabilities was defined as the final detection probability, and the optimal search path was obtained upon reaching the 1 000th generation because of the simulation utilizing the directional component genes to allow the searcher properly to search for the target as the generations went on. Furthermore, the proposed algorithm was assessed as more efficient by comparing the results of the proposed algorithm with the results of the random search.

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