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# A Novel Bio-Inspired Path Planning for Autonomous Underwater Vehicle for Search and Tracing of Underwater Target

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***Abstract*— Underwater search and tracing is a complex engineering problem, due to various factors, such as unpredicted oceanic environment, poor communications, underwater navigations. Therefore, to accomplish a challenging mission an autonomous underwater vehicle (AUV) cooperation is needed. This study focuses on the search and tracing of an underwater target, based on an improved cooperative path planning model. To achieve the possible results, the mission is divided into search and tracing phases aiming to maximize the search space thus reducing terminal error respectively. The developed method is inspired by bio-inspired Improved Whale Optimization Algorithm (IWOA) based method, hence modeling improved path for autonomous underwater vehicle followed by simulations of various parameters for experimentation, such as maneuverability and communication ranges between autonomous vehicles, in a distributed or centralized scenarios. For the above process, the IWOA is compared with the improved particle swarm optimization (IPSO) algorithm for different parameters for the search and tracing of the underwater target. The simulated results exhibit that the proposed method presents superior results for the search and tracing phase, which also increases the computational performance together with well-achieved optimization on large-scale complex problems for cooperative path planning.**

**Keywords— Evolutionary Computing, Meta-Heuristic Algorithms, Improved path planning, Acoustic communication, Autonomous vehicles, Microwave Communication.**

## I. INTRODUCTION

For autonomous vehicles to accomplish several complex tasks to work cooperatively as related to a single autonomous vehicle, for which the rate of success for a mission could be enhanced. Cooperation could be accomplished by single and combination of different autonomous vehicles. For complex missions, cooperation among vehicles was employed. The cooperation among autonomous vehicles performs different roles depending on the demand and characteristics of autonomous vehicles. In this study, the cooperation among different autonomous vehicles system was employed to perform a search and tracing of an underwater target, thus the phenomenon of cooperation between autonomous vehicles was considered. To have efficient cooperation between different autonomous vehicles, autonomous vehicles could have effective communication by saving power, measurement of morphodynamic processes [1] could be done by autonomous vehicles and, so on. Autonomous ground vehicles are employed to detect roads and obtain multiple features of large datasheets from different images. A new multiple-task assignment and path planning problem for surface autonomous vehicles based on the improved self-organizing map and improved genetic algorithm [2] is proposed. The flight trajectory from starting point to endpoints of autonomous vehicles is generated, and the safety plus efficiency was increased by GIS and GPS mapping for path planning of autonomous vehicles [3]. A group of autonomous vehicles are commonly employed for search and tracing missions. Data collection, maintenance of submarine fiber cable, surveillance and security of oil and gas facilities, emergency response and, infrastructure inspections are few applications of the AUVs. Comparing the studies of single autonomous vehicles, the cooperation among different autonomous vehicles was comparatively rare. For air and surface autonomous vehicle systems, UAVs take the ground images from the air, which are transferred to the ground vehicle for the construction of ground mapping for explorations [4] and to enhance the recognition of obstacles. The monitoring, detection, and cleaning of different marine time regions for autonomous vehicles can be resolved using HMDC-System [5] which was useful for communication as well. For path planning of autonomous vehicles, a Genetic algorithm was employed for the starting to the ending point. The path planning and autonomy of autonomous vehicles is a significant matter for a complex atmosphere. For uniform distribution, exponential attenuation, inertia weight, and learning factor IPSO could achieve better results [6]. With higher precision for optimal flight path for UAV, the required path is divided into several segments which could change the

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complex path into a low dimensional path using IPSO[7] to enhance the probability of global search ability. The present traditional bio-inspired algorithms for path planning are hard to meet the progressively complex environment and mission requirements. To enhance the efficiency improved particle swarm algorithm (IPSO) was proposed [8]. In recent times the autonomous guided vehicles are used progressively for transportation purposes, IPSO based path planning was proposed [9] to obtain the desired path for the autonomous guided vehicles. The communication between AUV and UAV was prohibited when the AUV is underwater for security concerns. They could only transfer data when the AUV is overhead the water surface. The coordination among multiple AUVs and a single autonomous vehicle cooperatively performing an ocean exploration [10]is proposed for the determination of the communication process between autonomous vehicles, which enhances the radius of the search area while decreasing the sortie time of autonomous vehicles. An improved cooperative localization method based on Acoustic Round Trip- Ranging was employed to enhance the communication with coordinated time for surface and underwater vehicle systems[11]. As stated above, the search and tracing mission of the underwater target could be executed by a single autonomous vehicle system or by a cooperative autonomous vehicle system. Although there are some shortcomings, surface autonomous vehicles and AUVs have a comparatively fragile capability for search [12] due to terrain-based navigation, and the communication among autonomous vehicles was ineffective and fatigue analysis is studied in [13]. In this study, a novel bio-inspired cooperative autonomous vehicles system is employed to counter the above condition and hence improving the efficiency to complete the mission on time. Up to now, such an autonomous vehicles system is seldom in use. The key achievements of this study work could be determined as follows:

i. The development of a novel bio-inspired cooperative autonomous vehicle system, which determines the information and communication phenomenon among the autonomous vehicles during a mission.

ii. The construction of a prototype for search and tracing of an underwater target for real-time.

iii. The speed of autonomous vehicles is defined by kinetic equations of the particle and the maneuverability of autonomous vehicles is described. To predict the position of an underwater target, the Kalman filtering is used. The constraints for communication and detection are added. Moreover, optimization ranges for AUV in search and tracing phase the radius of searching was maximized and tracing is minimized to obtain optimal results.

iv. A novel bio-inspired improved path planning algorithm for autonomous vehicle systems was established. A centralized scenario is proposed for the search phase with randomly simulated results, so to decrease the complications of computing the search radius by autonomous vehicles. In the tracing phase, for a distributed scenario, an improved whale optimization algorithm is proposed that ensures an optimal collision-free path[14] in different constraints.

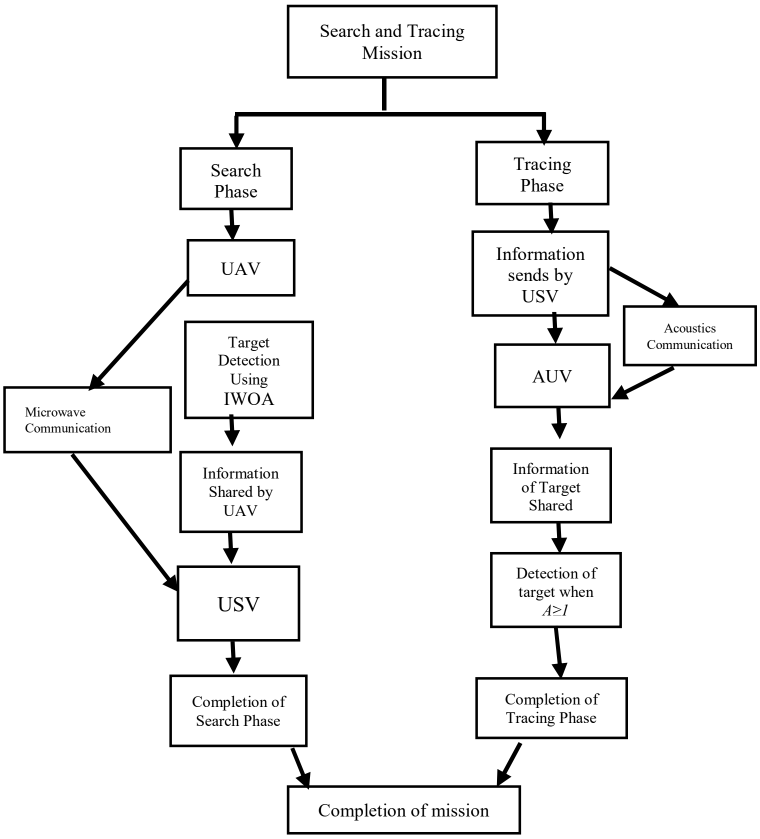

Fig. 1 Working Architecture among Autonomous Vehicles for search and tracing of underwater target

## II. BRIEF EXPLANATION OF THE SEARCH AND TRACING FOR AUTONOMOUS VEHICLES

The search and tracing mission is completed by autonomous vehicles, working with cooperation to search for an underwater target. The search phase goes for completion when the underwater target is identified by one of the autonomous vehicles. After that, the information about the position of an underwater target is sent to the AUV, and the underwater target could be traced by AUV. The mission will not end unless the displacement between the AUV and the underwater target is less than a threshold value. For the above-given process, a surface autonomous vehicle acts as a junction between the UAV and AUV since communication between AUV and UAV is prohibited. The situation for a given mission can be concluded as discuss in Fig. 1

The autonomous vehicles work together in a centralized scenario for the search phase, and the underwater target might be detected by one of the autonomous vehicles. According to the working architecture of autonomous vehicles in the tracing phase, the autonomous vehicles could plan their paths in a distributed mode.

## III. METHODS OF MODELLING FOR THE AUTONOMOUS VEHICLES

### *A. Kinetic Model and Motion Constraints of Autonomous Vehicles*

The autonomous vehicles are regarded to be particles circulating about 3D space. For the ground mode, the surface level of the ocean is well-defined in the OXY plane, the Z-axis is in the upward direction. The kinetic equation for autonomous vehicles is as follows:

$$\begin{cases} \dot{x} = S\cos\vartheta\cos\theta \\ \dot{y} = S\cos\vartheta\sin\theta \\ \dot{z} = S\cos\vartheta\sin\theta \\ \dot{\theta} = p \\ \dot{\vartheta} = \gamma \\ \dot{S} = \beta \end{cases} \tag{1}$$

where (*x, y, z*) and *S* represent the initial position and speed of the autonomous vehicle, correspondingly. $\vartheta$ and $\theta$ are gliding and inclination angles, $\gamma$, and $p$ are the angular values and $\beta$is the acceleration. From Eq. (1) the control variable of an autonomous vehicle can be defined as $\mathbf{a} = [\gamma\ p\ \beta]^T$ and the state variable of the autonomous vehicle can be defined as

$\mathbf{b} = [x\ y\ z\ S\ \theta\ \vartheta]^T$

### *B. Maneuvrability Constraints of Autonomous Vehicles*

Maneuvrability of the autonomous vehicle shows the rate of change of speed, height, and direction of motion. Autonomous vehicles move at a constant altitude and float over the surface of the ocean. The values of$p$, $\gamma$, and $\beta$ for autonomous vehicles are stated below:

$$\begin{cases} p_{UAV,USV,AUV} = 0 \\ \left|\gamma_{UAV,USV,AUV}\right| \le \gamma_{UAV,USV,AUV\,max} \\ \left|\beta_{UAV,USV,AUV}\right| \le \beta_{UAV,USV,AUV\,max} \end{cases} \tag{2}$$

$$\begin{cases} p_{Traget} = p_{Target} \\ \left|\gamma_{Target}\right| \le \gamma_{Target\,max} \\ \left|\beta_{Traget}\right| \le \beta_{Target\,max} \end{cases} \tag{3}$$

The movement of the underwater target is not defined, but its initial position can be determined. For a common situation, the underwater target is moving randomly. Eq. (2) defines the random values of an underwater target. The initial position of the underwater target is identified by autonomous vehicles if it is located in the given range of detection, and its future position could be predicted -based on the data collected. The Kalman filtering equations for the motions of the underwater target are defined below:

$$\begin{cases} Y(m) = BY(m-1) \\ Z(m) = KY(m) \end{cases} \tag{4}$$

$$\begin{cases} w(m) = w(m-1) + s(m-1)T + \frac{1}{2}\beta(m-1)T^2 \\ s(m) = s(m-1) + \beta(m-1)T \\ w_z(m) = w(m) + s(m) \end{cases} \tag{5}$$

here *T* is taken as the observed time interval from $m-1$ to $m$, $w_z$ is detected value and w and s are taken as values for initial position and speed. The uniform motion of the underwater target during time *T* is shown in Eq. (4). Two types of equations that shows the motion of the target. Eq. (1) shows the actual motion while Eq. (4) is used to find the future motions of the underwater target using the Kalman Filtering method [15].

### *C. Constraints in Each Phase for Autonomous Vehicles*

#### *1) Space Constraint for Autonomous Vehicles:*

The autonomous vehicles have to move within a given possible three-dimensional space is given by

$$\begin{cases} x_i \le x_{UAV,USV,AUV} \le x_j \\ y_i \le y_{UAV,USV,AUV} \le y_j \\ z_i \le z_{AUV,Target} \le 0 \\ z_{AUV} = const \\ z_{USV} = 0 \end{cases} \tag{6}$$

where $x_i$,$x_j$ ,$y_i$ and $y_j$ are the bounded values in the OXY plane, and $z_i$ is the threshold depth the autonomous underwater vehicle can jump

#### *2) Speed Constraint for Autonomous Vehicles:*

The autonomous vehicles should operate accordingly to given conditions. For that, the maximum speed for each autonomous vehicle is given by

$$\begin{cases} |S_{UAV}| \le S_{UAV\,max} \\ |S_{USV}| \le S_{USV\,max} \\ |S_{AUV}| \le S_{AUV\,max} \\ \left|S_{Target}\right| \le S_{Target\,max} \end{cases} \tag{7}$$

#### *3) Time Constraint for Autonomous Vehicles:*

The AUV must be nearer to the target as much as possible for the closing time interval. In order to end the search and tracing phase, the displacement for the AUV and the underwater target should remain smaller than the approached value is shown below:

$$|D_{AUV}(t_f) - D_{Target}(t_f)| \le d_{AUV-Target} \qquad 8)$$

where $D_{AUV}$ and $D_{target}$ are the initial locations of AUV and underwater target, $t_f$is the closing time interval. The operator | ▪ | in Eq. (8) is used for the calculation of displacement between given points, $d_{AUV-Target}$is the given value between AUV and underwater target.

#### *4) Communication and Detection Constraint for Autonomous Vehicles:*

The detection radius for the autonomous vehicles is given as $d_{detect}$ Moreover, for normal communication among the autonomous vehicles, the displacement among autonomous vehicles must be reduced.

### *D. Optimization Range for Search and Tracing Phase*

For the search phase, the search area for autonomous vehicles must remain larger to enhance the possibility of the target detection. For the tracing phase, the displacement among the AUV and the underwater target must remain smaller to decrease a terminal error. The two phases could be expressed as follows:

$$\begin{cases} L_1 = \max\big((S_{UAV} \cup S_{USV} \cup S_{AUV}) \cap S_z \le 0\big) & (9a) \\ L_2 = \min\Big(\big|D_{AUV}(t_f) - D_{Target}(t_f)\big|\Big| & (9b) \end{cases}$$

where $S_{UAV}$,$S_{USV}$,$S_{AUV}$ are the search space of the autonomous vehicles and $S_{z\le 0}$ is the area underneath the water surface.

## IV. BIO- INSPIRED PATH PLANNING FOR SEARCH AND TRACING OF UNDERWATER TARGET

The search and tracing phases are comparatively independent; hence both the phases were separately solved. Model predictive control was followed for online planning. A bio-inspired improved Whale Optimization Algorithm (IWOA) is proposed to achieve paths for autonomous vehicles.

### *A. Maximization of Search Phase on Randomly Based Simulated Experiments*

To enhance the probability of the target detection in underwater the search radius was maximized. In order to achieve such scenario an approximation technique was developed which was based on randomly simulated experimentations. The altitudes of underwater space such as height, length and breadth are divided into$I_x$,$I_y$, and $I_z$ parts and the values of $I_x$, $I_y$, and $I_z$ could be changed for online computation to meet the required demand. For a particular location of underwater target, the combination of autonomous vehicles, the range of search radius could be measured by several points located into the given search radius. The optimization range given in Eq. (9a) was upgraded as given below:

$$L_1 = \min\left((I_x + 1) * (I_y + 1) * (I_z + 1) - I_{sphere}\right) \quad (10)$$

where $I_{sphere}$ are the several points located in the search radius combined by autonomous vehicles.

### *B. A Novel Improved Path Planning Approach for the Tracing Phase*

For autonomous vehicles the paths were defined randomly in a distributed scenario, a novel improved path planning approach was established to work with an organized way for each time interval. For each time interval $m$, the autonomous vehicle that has identified the target indicates its present position. The tracing mission is executed by AUV, hence planning the path for it. To get better results among autonomous vehicles, the constraints shall not be added. AUV defines the path, and position of an underwater target using optimization range as given in Eq. (9b). Due to this autonomous vehicles plan their path simultaneously. Comparing the path planning of autonomous vehicles during the communication the constraints for displacement between surface vehicle and AUV were put for further approach. The optimization range for surface autonomous vehicles and autonomous air vehicles is given as

$$\begin{cases} L_{2USV} = \min\left(d_{USV-Target}\,(m + 1)\right) \\ L_{2UAV} = \min\left(d_{UAV-Target}\,(m + 1)\right) \end{cases} \quad (11)$$

where $d_{USV-Target}(m + 1)$, $d_{UAV-Target}\,(m + 1)$is the displacement between surface and air autonomous vehicle and the target with time interval $(m + 1)$.

### *C. Implementation of Improved Bio-Inspired Whale Optimization Algorithm for Cooperative Path Planning*

Meta-heuristic algorithms are getting more and more popular for solving path planning problems. Improved Whale optimization algorithm (IWOA)[16], a meta-heuristic algorithm could be used for path planning[17] of autonomous vehicles. IWOA could be employed in online optimization problems very effectively [18]. There are several strategies to increase the ability, and make modifications for online optimization [19]. In contrast to the search phase in a centralized scenario, the control variables are defined $\boldsymbol{a}^1$= $[\gamma_{UAV}\ \beta_{UAV}\ \gamma_{USV}\ \ \beta_{USV}\ p_{AUV}\ \ \gamma_{AUV}\ \beta_{AUV}]^T$ for the tracing phase the system is organized in distributive scenario, the control variables for each autonomous vehicle are defined as $\boldsymbol{a}^2_{UAV}$= $[\gamma_{UAV}\ \beta_{UAV}]$, $\boldsymbol{a}^2_{USV}$= $[\gamma_{USV}\ \beta_{USV}]$, $\boldsymbol{a}^2_{AUV}$= $[p_{AUV}\ \gamma_{AUV}\ \beta_{AUV}]$. These control variables are upgraded with respect to IWOA algorithm. In the end, an incriminated time duration is employed to the position up gradation, given as $a_j(m + 1)$= $a_j(m)$+$\Delta a_j\ (m)T_i$ where $T_i$ is time duration.

For every iteration time, an underwater target upgrades its position with reference to a randomly chosen target or the best result achieved. To enhance the performance of the WOA algorithm [20], the standard WOA is improved under three aspects, initial population, convergence factor, and mutational operations, applied to the path planning by proposing a new judgment criterion to get improved WOA (IWOA) [21]. These three modifications could increase the global and local search, which was compatible with the given iterations time, hence the cost of computation was decreased. To get better results, the control variables should be limited with small iterations time intervals and therefore, the ending time interval for path planning was decreased. Eq. (9)-(11) shows the quality of solutions.

## V. SIMULATIONS AND RESULTS

To enhance the effectiveness of the proposed improved path planning technique of underwater target, experimental simulations were executed for random values. For the first condition, several initially random positions of an underwater target were taken into account, and the proposed method was able to improve for the given conditions. For the second condition, parameters such as displacement and time interval of autonomous vehicles and underwater target for the proposed bio-inspired algorithm for an autonomous vehicle were compared with parameters of the previously employed algorithm. All the obtained results are run on MATLAB 2019b with a system (equipped with Open GL 3.3 with 2 GB GPU memory). For the IWOA algorithm, the swarm scale is

10 and the maximum repetition time interval is 20. Key point values are set as $d_{detection}$ = 1000 m, $d_{UAV-USV}$ = 3000 m, $d_{USV-AUV}$ = 500 m and $d_{AUV-Target}$ = 2 m, accordingly.

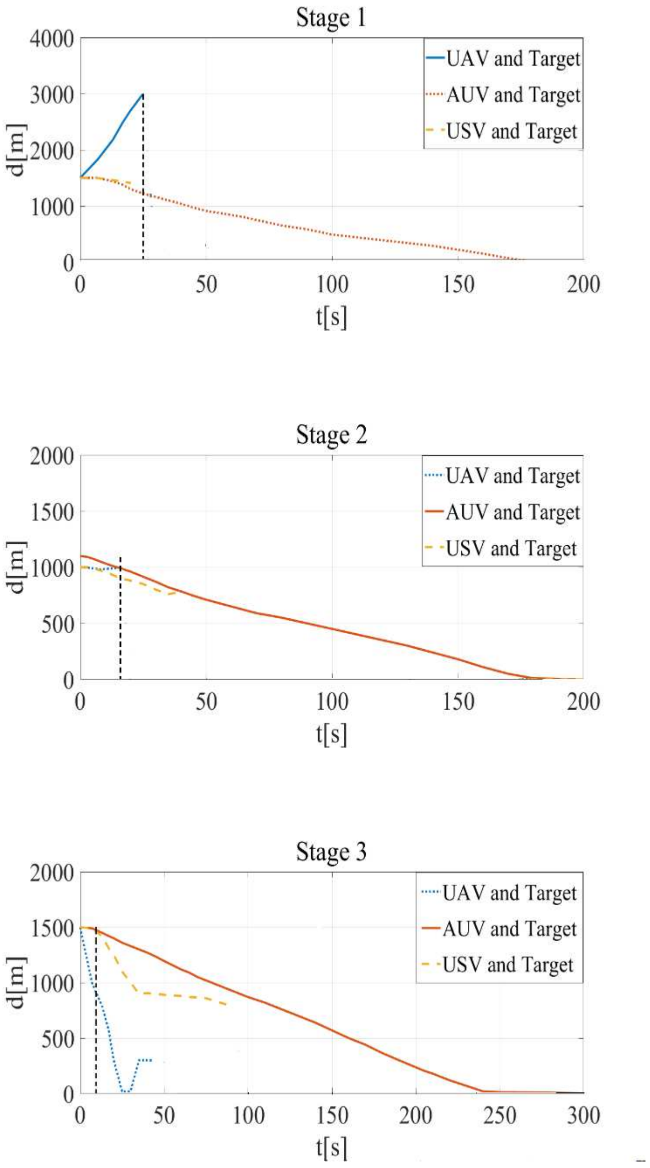

Fig. 2. Displacement among autonomous vehicles and underwater target at three stages.

### A. *Improved Results for Search and Tracing of Underwater Target during Different Stages*

Initially, several random positions of the underwater target were taken into account for the final key results. During the three stages, the AUV can trace the target successfully with the least time interval. To show that the achieved improved results can fulfill the desired given constraints, the displacement among autonomous vehicles, underwater target and the displacement among different autonomous vehicles, are shown in Figs. 2 and 3 respectively.

The black dotted lines in an upward direction show the points among two phases. For stages 1, 2, and 3, the different autonomous vehicles detect the target first, and the three stages are then responsible for the search phase as well. To ensure stable communications among different autonomous vehicles, the displacement among the autonomous vehicles remains within the allowed ranges.

Table I. shows the comparison between the proposed bio-inspired algorithm and the previously employed algorithm for detection and tracing of underwater target and time interval for different stages as mentioned above.

For all three stages, the target can be traced within the required time. Table I shows that it requires the least time to accomplish the mission in Stage 1 as compared to the previously employed algorithm. AUV first detects the target and then traces it with a least time as compared to the previous time interval.

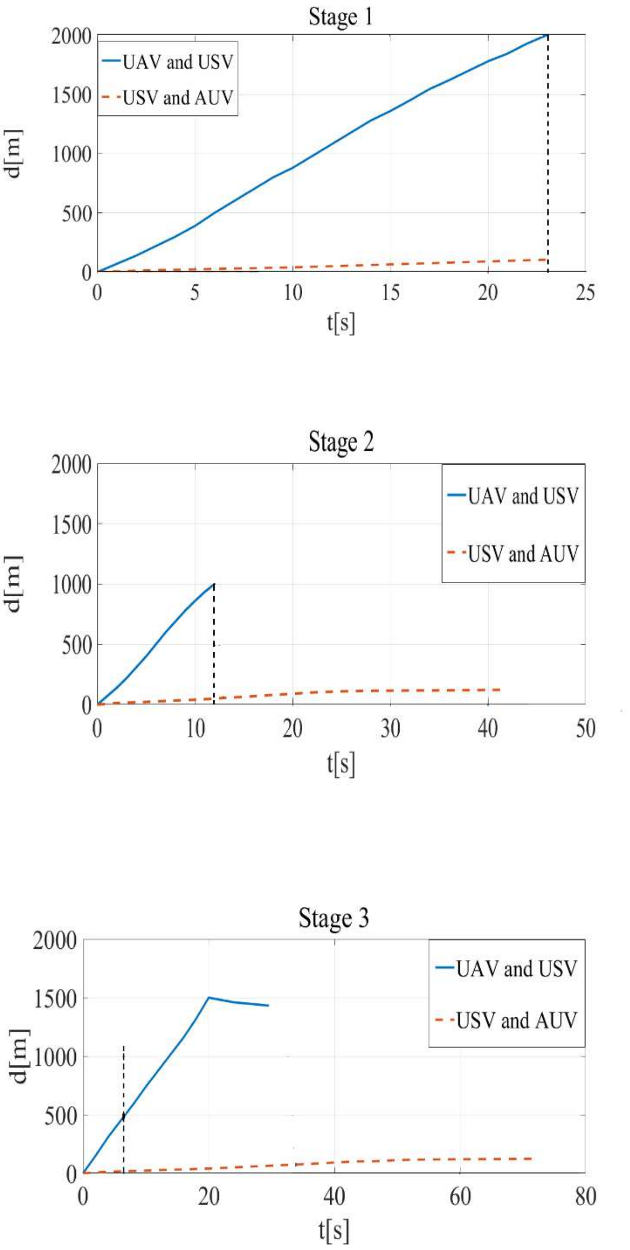

Fig. 3. Displacement between different autonomous vehicles in three stages

For Stage 2, the surface autonomous vehicle first finds the underwater target and sends its location to AUV with the least time intervals. The underwater target is detected by AUV at 41s less than the previous time interval, then starts to trace it. For more specific conditions, an autonomous air vehicle can find and locate the underwater target with the least interval of time as associated the other two stages because of its high-altitude speed, which permits it to insure more area for the given time interval.

Table I Comparison of parameters using Proposed Bio-Inspired and the previously employed algorithm

| | IPSO Algorithm [22] | | | IWOA Algorithm | | |
|---|---|---|---|---|---|---|
| | Stag1 | Stag2 | Stag3 | Stag1 | Stag2 | Stag3 |
| Time Interval for Detection of Underwater Target | AUV= 22 s | USV = 13s<br>AUV = 43s | UAV = 7s<br>USV = 33s<br>AUV = 76s | AUV= 20sec | USV = 11s<br>AUV = 41s | UAV = 5s<br>USV = 31s<br>AUV = 74s |
| Closing Time Interval of the Mission | 184s | 200s | 298s | 182s | 198s | 296s |
| Displacement of AUV from Underwater Target | 0.83m | 0.69m | 0.45m | 0.82m | 0.6m | 0.43m |

From Table I it is concluded that the proposed bio-inspired algorithm (IWOA) has 2% more efficiency with respect to time interval for target detection as well as closing time interval for mission as compared to previously employed algorithm (IPSO). It also decreases the displacement of AUV from underwater target, hence the range of target detection is 2% reduced.

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### B. *Comparison of Various Parameters of Search and Tracing Between Proposed Bio-Inspired Algorithm and Previously Employed Algorithm*

A cooperation among surface autonomous vehicle and the AUV system was presented to achieve the same goal. The initial points are taken similarly in all three stages. In Fig.4 the results of displacement between both the autonomous vehicles and underwater target are shown by comparing the results of the bio-inspired algorithm and previously employed algorithm.

To have normal communication among surface autonomous vehicles and AUV, the displacement between them has been reduced to 500m. Fig.4 shows that the target is identified first by the surface autonomous vehicle at 24s, and then AUV finds at 130s less than the previous time interval. AUV accomplishes the tracing task at 319s, and the terminal error is 1.93m. Comparing the results in Table I, clearly shows that the search and tracing ability of the previously employed algorithm is less than the proposed bio-inspired algorithm.

The obtained parameters using the proposed bio-inspired algorithm for cooperation among autonomous vehicles show better results for search and tracing of an underwater target as compared to the previously employed algorithm[22]for search and tracing of an underwater target as shown in Table I.

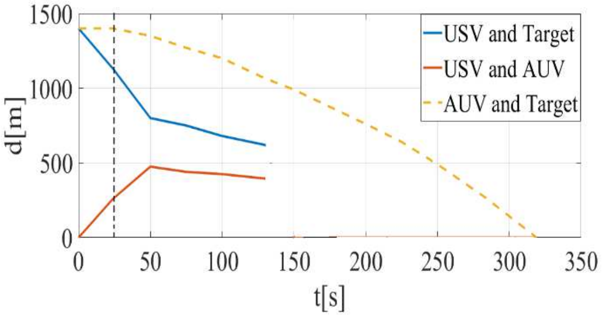

Fig. 4. Displacement of AUV and target, USV and AUV, and USV and Target.

## VI. CONCLUSIONS

The cooperative improved path planning for search and tracing of an underwater target is studied in this paper, and the required task was accomplished by the comparison among the proposed bio-inspired algorithm and previously employed algorithm. The accomplished results show that previously employed algorithm (IPSO) for cooperation among autonomous vehicles had weak ability in search and tracing of an underwater target, while the proposed bio-inspired algorithm (IWOA) for cooperation among autonomous vehicles for search and tracing of an underwater target has superiority over it. This bio-inspired algorithm (IWOA) can be used for intelligent traffic management systems and communications among autonomous vehicle.

Firstly, the cooperation of autonomous vehicles was presented. For the kinematics modeling, the motions of autonomous vehicles were defined by kinetic equations, and the location of an underwater target was predicted using the Kalman filter method. The entire mission was divided into two phases, and the given variables were upgraded under the given framework. The main idea of using the proposed bio-inspired algorithm was to reduce the time interval for search and tracing of an underwater target as well as terminal error and to maximize the searching area for autonomous vehicles. To resolve the established cooperative improved path planning model, model predictive control was followed for online planning, a centralized and a distributed scenarios were established to create the improved paths for the two phases correspondingly using a novel bio-inspired whale optimization algorithm.

For simulation studies, various stages were introduced but the proposed approach was capable to overcome various complex conditions successfully. The above study shows that the proposed bio-inspired algorithm for cooperation among autonomous vehicles is more effective than the previously employed algorithm for the search and tracing of an underwater target. For the future, the more complex tasks could be accomplished using the bio-inspired algorithm for cooperation among autonomous vehicles, and this could be employed for improving resource management for autonomous underwater gliders, applied to remotely controlled autonomous underwater vehicles could also be used for path planning scheme for AUV flock-based model for internet-of-underwater-things system to enable transport and smart ocean for future based work for search and tracing of underwater using such improved conditions. Experiments based on hardware and software could be employed to show the reliability and the durability of the method illustrated.

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