Proposal of a Swarm Intelligent Underwater Glider System for Long-term Three-dimensional Wide-area Ocean Observation

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Abstract

The ocean is facing serious threats due to global warming and ocean acidification. In order to conserve the ocean, it is very important to understand the ocean environmental situations correctly over a long term and wide area. In this research, the authors propose a swarm intelligent underwater glider system for ocean observation. The operation simulation within Japan's Exclusive Economic Zone (EEZ) verified the validity and effectiveness of the proposed system, and the number of underwater gliders was estimated for requiring to realise continuous and even observation of Japan's EEZ.

Keywords: Autonomous Underwater Glider, Swarm intelligent underwater vehicle, Path search, SOARER

1. Introduction

One of the Sustainable Development Goals (SDGs) adopted by United Nations in 2015 is sustainable management and protection of marine and coastal ecosystem from pollution in goal 14: LIFE BELOW WATER. In order to maintain marine and coastal ecosystem and to comprehend ocean condition accurately, it is necessary to establish a long-term marine survey system for the entire sea area. However, it is not easy to investigate in special underwater environments. In conventional survey method, research ships, buoys, floats, Remotely Operated Vehicles (ROVs), and Autonomous Underwater Vehicles (AUVs). However, manned research submersible and ROV are not suitable for wide area ocean survey because the movable range is limited. AUVs can cruise freely under water, but it has limited uptime due to the large battery consumption.

It is widely known that Autonomous Underwater Glider (AUG) has an ability of long-term and wide-area operation by consuming less energy because it propels using fluid dynamic force acting on fuselage and wings by controlling underwater weight and attitude angle while diving and surfacing. In this research, we propose a three-dimensional wide-area ocean observation system using swarm intelligent underwater vehicles centred on multiple AUGs suitable for realising a long-term and continuous operation. It is necessary to operate a huge number of AUGs during the same term expanding over the entire observatory sea area. Some methods of operation while patrolling the set route[1)] and survey using some vehicles while following the leader vehicle[2)] have been proposed.

In this paper, the authors propose a method of searching the movement path of own vehicle. Furthermore, swarm intelligence for AUGs is introduced for realising the reluctant cooperative behaviour.

In addition, we try to verify the effectiveness of the proposed method by operative simulation within the Japan's Exclusive Economic Zone (EEZ), and to estimate the number of vehicles required to achieve observation of Japan's EEZ. At first, the autonomous underwater glider "SOARER" used in this paper is introduced in section 2. Next, the methods of optimal path search and cooperative behaviour are described in section 3. The operative simulation in Japan's EEZ is demonstrated in section 4. Finally, conclusions are described in section 5.

2. Autonomous Underwater Glider with Independently Controllable Main Wings

2.1. *SOARER*

AUG is an underwater research vehicle suitable for a long term operation. In this research, the autonomous underwater glider with independently controllable main wings named "SOARER"[3, 4] which is developed with the aim of improving maneuverability was used. SOARER has characteristics which can be changed roll angle and gliding angle appropriately by controlling its main wings. The snapshot of the SOARER glider is shown in Fig.1 and specifications are listed in Table 1.

SOARER is mounted three sensors, six actuators and an environmental observation profiler. Fig. 2 shows system configuration of SOARER. The mounted sensors are IMU (Inertial Measurement Unit), GPS (Global

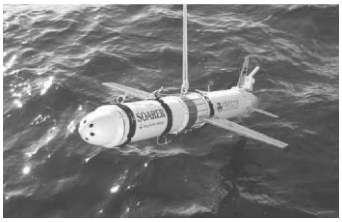

Fig. 1 Snapshot of SOARER.

Table 1 Specifications of SOARER.

Items	Value
Length	2.416 m
Breadth	1.460 m
Height	0.505 m
Mass	Abt. 80 kg
Wing profile	NACA0009
Wing chord at tip/root	0.13 m/0.26 m
Volume of ballast tank	2.01 L
Maximum operational depth	1500 m

Positioning System) and a depth sensor. The actuators are

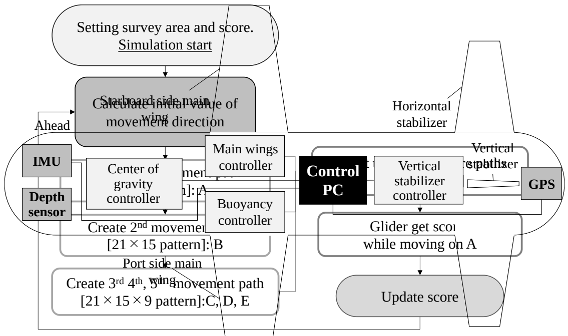

Fig. 4 Outline of path search method.

Fig. 2 System configuration of SOARER.

consisted of a centre-of-gravity controller, a buoyancy controller and four wing controllers. The centre-of-gravity controller controls SOARER's pitch angle by shifting the movable weight to ahead and astern. The buoyancy controller controls underwater weight by injecting and draining water to dive or surface. Wing controllers are vertical and horizontal stabiliser, starboard and port main wings controller. Vertical and horizontal stabilisers mounted behind the vehicle controls yaw and pitch angle by controlling the vertical and horizontal wing like rudder and elevator. Right and left main wings mounted on starboard and port side of the centre of vehicle control its gliding angle and bank angle. For controlling its gliding angle, both main wings can be rotated in the same phase to change its hydrodynamic force around wings. Furthermore, the bank angle can be controlled by rotating in the opposite phase to change its hydrodynamic force acting on each wing.

The environmental observation profiler "RINKO-Profiler" that measures dissolved oxygen (DO), depth, temperature, electrical conductivity, freshwater EC, salinity, chlorophyll, turbidity in seawater is mounted on the SOARER glider.

2.2. *Disturbance compensation underwater*

AUG cannot be positioning underwater using GPS, because the radio wave is not transmitted in the water. Therefore, tracking error increases because AUG cannot recognise disturbance in the sea. In this research, underwater position and disturbance compensation are estimated using the dead reckoning which estimates the position from the heading angle and the speed of the vehicle.

The position is estimated by dead reckoning, and the disturbance compensation uses this estimated vector as shown in Fig. 3. AUG dives to shallow depth for

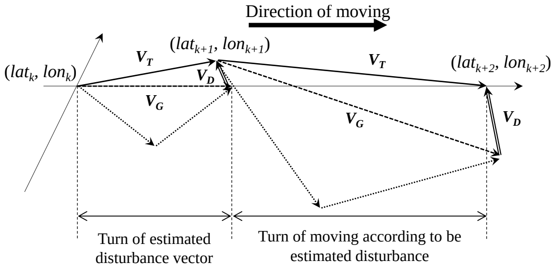

Fig. 3 Estimated disturbance vector.

estimating *disturbance vector*. This *disturbance vector* is calculated from *guessed vector* obtained from moving direction and speed of movement, and *true vector* indicating actual moving direction. In accordance with the estimated disturbance, AUG moves to next surfacing point considering *disturbance vector* during diving to operational depth.

Disturbance vector is estimated as follows:

$$\boldsymbol{V_T} = (dlat,\ dlon) \tag{1}$$

$$\begin{aligned} dlat &= (lat_{k+1} - lat_k)\cdot 60\cdot 1852 \\ dlon &= (lon_{k+1} - lon_k)\cdot cos(m.l)\cdot 60\cdot 1852 \\ m.l. &= (lat_{k+1} + lat_k)/2 \end{aligned} \tag{2}$$

$$\boldsymbol{V_D} = \boldsymbol{V_T} - \boldsymbol{V_G} \tag{3}$$

where, $\boldsymbol{V_G}$ is *guessed vector*, $\boldsymbol{V_T}$ is *true vector*, $\boldsymbol{V_D}$ is *disturbance vector*, (lat_k, lon_k) is position of starting gliding, (lat_{k+1}, lon_{k+1}) is the estimated surfacing position. *True vector* is calculated by middle-latitude diving as following Eq. (2), and *guessed vector* is estimated by dead reckoning. *Disturbance vector* is calculated by Eq. (3).

3. Optimal Path Search Algorithm

3.1. *Outline of optimal path search algorithm*

For realising wide-area ocean observation with multiple AUGs, it is necessary to select and determine their cruising route through sea areas. Fig. 4 shows outline of optimal path search algorithm. In this research, the optimal path search is realised by iterational local search method which repeats optimal solution search on neighborhood and random transformation of initial value. Every vehicle moves while correcting path planning every surfacing to the sea surface, because AUG cannot surface at the planned point. This algorithm is consisted of three parts, setting survey area part, path search part, move along the optimal route and updating score part. The optimal path is searched by repeating these parts.

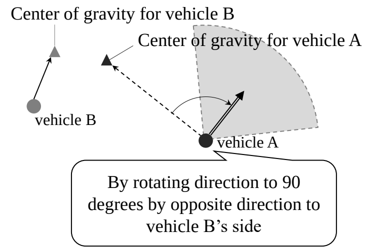

Fig. 6 Reluctant cooperation by vehicle A.

The first part is setting the survey area. The survey area is divided into cubes which are given the score according to importance of the area. The survey area is divided every 1 degree in horizontal X-Y direction, and depth in Z direction is divided as shown in Table 2.

The second part is creating some paths and searching the optimal path from the created paths. *Initial value of movement direction* that is the direction to create path is calculated from the centre of area score which is sum of 9 cubes' vertical scores as follow in Table 2 around the vehicle. Therefore, candidate paths are created toward *initial value of movement direction* from start point as shown in Fig. 5.

Next, paths are created from start point. In this algorithm, 1st movement paths are created from start point, and next movement paths are created from the tip of previous movement paths. Direction of created path is not changed while cruising in the water. Therefore, paths are created in a straight line and increasing on every ascend point like a branch. However, it is high calculation cost that paths

Table 2 Divided depth of the survey cube.

No	Depth[m]	No	Depth[m]	No	Depth[m]
1	0-50	2	50-100	3	100-200
4	200-400	5	400-600	6	600-800
7	800-1000	8	1000-1250	9	1250-1500

Table 3 Yaw angle path pattern.

Number of gliding	Yaw angle						
1:	–90	–60	–30	0	+30	+60	+90
2:		–90	–45	0	+45	+90	
3, 4, 5:			–90	0	+90		

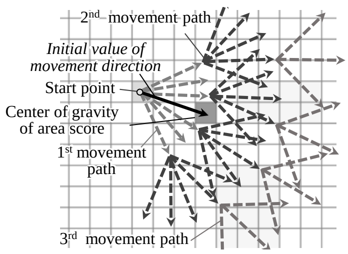

Fig. 5 Creating paths for search.

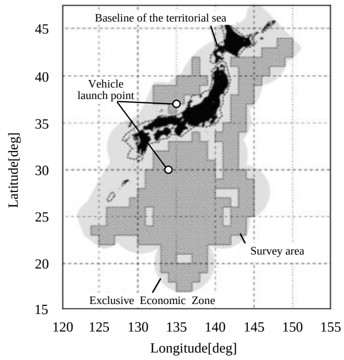

Fig. 7 Survey area based on Japan's EEZ.

are created in large quantities, and calculation power of the mounted PC in AUG is not high to reduce energy consumption. In this research, paths are created for 5 diving times, and the number of created paths is changed gliding angle and yaw angle for every diving times. The number of created path pattern are 1st movement is 3 gliding angle patterns and 7 yaw angle patterns, 2nd movement is 3 gliding angle patterns and 5 yaw angle patterns, and 3.4.5th movement is 3 gliding angle patterns and 3 yaw angle patterns. Yaw angle patterns are changed for every diving times as shown in Table 3, and gliding angle of path is changed to 8, 15, 20 degrees. When the paths have be created, the got scores as passing while 5 diving times is calculated by simulation, and it is assumed that paths while 5 diving times with the highest got score is the optimal paths as most important route.

The final part is moving on the optimal route and updating score of surveyed cubes. AUG moves on the only 1st movement path of optimal paths selected in the second part. When the movement of AUG to the 1st movement path is completed, score of cubes passed through AUG is updated as surveyed cubes. Lastly, the algorithm returns to the second part and searches optimal path again. By the above method, the algorithm search for optimal route that preferentially passes through survey cubes with the highest scores without high accuracy position.

3.2. *Cooperative behaviour*

A lot of AUGs need to be operated efficiently to survey for a wide range. It is necessary to select a route to maintain an appropriate distance between vehicles to avoid collision or expand the survey area. In this research, a simple rule of the reluctant cooperative behaviour is adopted. AUGs are required "not to disturb other vehicles".

When an AUG approaches another vehicle, each AUG estimates the expecting score to get and decides which one should give way. If the distance between the vehicle and centre of area score position is shorter, many high score cubes are near the vehicle. By contrast, if this distance is longer, many high score cubes are far away from the vehicle. In this method, the vehicle with the shorter distance between the vehicle and centre of area score position keeps route. Furthermore, the vehicle with the longer distance gives way by rotating *initial value of movement direction* which is direction to search path method to 90 degrees in opposite side to other vehicle's position.

The outline of cooperative behaviour is shown in Fig. 6. Vehicle A and vehicle B are shown as circle, and the centre of area score is shown as triangle. When two vehicles are approaching within a certain distance as shown in Fig. 6, two vehicles calculate the distance of centre of area score. In this situation, vehicle A gives way to vehicle B because vehicle A's distance of the centre of area score is longer than the vehicle B's distance. Vehicle A gives way by rotating *initial of movement direction* which is direction to search path method to 90 degrees in the direction opposite side to position of vehicle B, and search optimal path toward the direction after rotation.

Furthermore, when more than two vehicles are approaching, *initial value of movement direction* of all approaching vehicles are changed to the outside like a repulsing. If n vehicles are approaching a certain distance, i th vehicle's *initial value of movement direction* which is $Co.[i]$ is shown as follows:

$$Co.[i]=(360/n)\cdot(i-1) \tag{3}$$

4. Simulation of Underwater Operation

4.1. *Setting of simulation*

In this section, operative simulation of many AUGs for Japan's EEZ is conducted to verify the effectiveness of the proposed method and to estimate the number of vehicles required to achieve continuous and even observation of Japan's EEZ.

Survey area is set based on EEZ as shown in Fig. 7. The survey area consists of two unconnected areas, "Japan sea area" and "Pacific Ocean area". These areas are set removing baseline of the territorial sea and island from EEZ. The vehicle's launch positions are shown circle in Fig. 7.

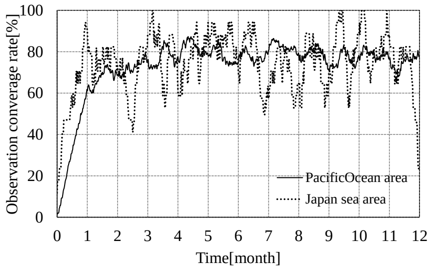

Fig. 11 Observation coverage rate.

The assigned score to the area and latest surfacing positions of all vehicles are managed by land base station. AUGs communicate to the land base station while sea surface to receive the position of other AUGs and send the data of survey seawater. The land station summarises received data of passing cubes and assigns score to area. This assigning score is reassigned after a certain period which is set 2 weeks after the score obtained in this simulation. The operational depth is set 1,500m, and the allowable approach distance between AUGs is set 50km. The simulation runs for a year, and the result of simulation is evaluated by an indicator of the observation coverage rate which is calculated by the number of areas passed within past 2 weeks.

4.2. *Result of simulation*

Figs. 8-9 show simulation results of Pacific Ocean area and Japan Sea area with every number of vehicles. Dashed line is the average observation coverage rate, plot of circle is the differential of observation coverage rate in Fig. 8. Fig. 10 shows tracks of simulation using 30 vehicles in Pacific Ocean area and 2 vehicles in Japan Sea area, for 1st -3rd month, 4th -6th month, 7th -9th month, 10th -12th month from the left. Leftmost figure which is tracks for 1st -3rd month shows that many vehicles expand to whole area over 3 months. Therefore, average observation coverage rate is calculated as an average value between 3rd -12th month after vehicles expanding whole area. Figs. 8-9 shows that observation coverage rate is increasing in proportion to increase the number of vehicles, and the rate converges to 90%.

In Japan Sea area, the rate converges to 90% when the number of vehicles more than 2 vehicles. Furthermore, it is necessary that the operating vehicle is more than 1 vehicle because when the vehicle fail, the survey of the area stops. From the above, the number of vehicles required for the survey of Japan Sea area is 2 vehicles. The average observation coverage rate is 77.2% using 2 vehicles in Japan Sea area.

In Pacific Ocean area, the rate converges to 90% when the number of vehicles more than 45 vehicles. The differential of observation coverage rate is wide variation between 30 and 35 vehicles as shown in Fig. 8. This variation show observation coverage rate decreasing significantly more than 30 vehicles.

From the above, the number of vehicles required to obtain a higher observation coverage rate with a smaller

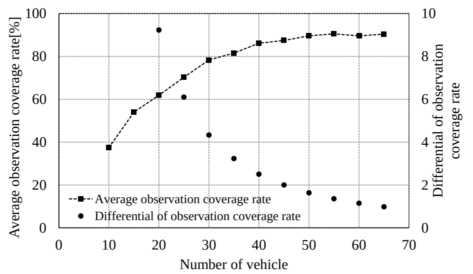

Fig. 8 Observation coverage rate of Pacific Ocean area.

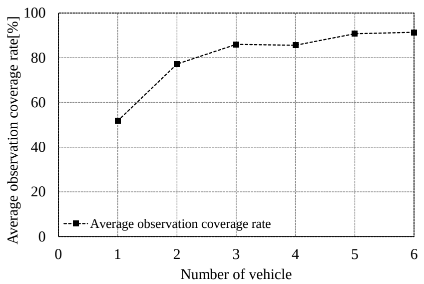

Fig. 9 Observation coverage rate of Japan Sea area.

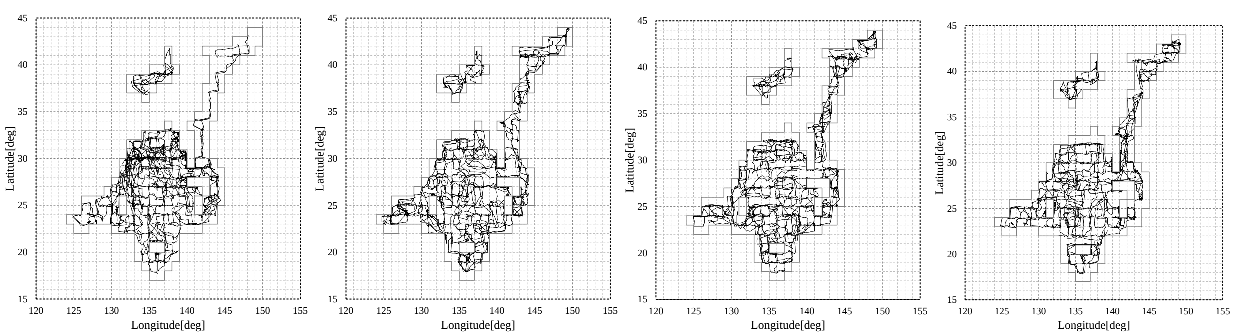

Fig. 10 Tracks every 3 months. (1st -3rd month, 4th -6th month, 7th -9th month, 10th -12th month)

number of vehicles is 30 vehicles. The average observation coverage rate is 78.3% using 30 vehicles in Pacific Ocean area.

Survey resolution is 1degree as shown Fig. 10 in this simulation. Observation coverage rate for a year is shown in Fig. 11. The survey has been continuously expanded to whole survey area, and it has confirmed that the constructed wide area observation system is effectiveness.

5. Conclusions

In this research, an observation strategy of a long-term wide-area sea area using a number of AUGs was proposed. Route search method from the surrounding situation was examined and wide-area ocean observation with AUGs was simulated to verify the effectiveness of the proposed method. The route search method was consisted of optimal path search algorithm and cooperative behaviour. The optimal path search algorithm was developed so that the AUGs pass preferentially through survey cubes with the highest scores without high accuracy position. High survey efficiency was achieved without the vehicle approaching excessively to adopt reluctant cooperative behaviour as swarm intelligence.

Finally, the effectiveness of the proposed method was verified, and the number of vehicles required for observation in Japan’s EEZ was estimated by operative simulation.

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