Formation Control Experiment of Autonomous Jellyfish Removal Robot System JEROS

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Abstract. The proliferation of jellyfish is threatening marine ecosystem and has caused severe damage to marine-related industries. An autonomous jellyfish removal robot system, named JEROS (Jellyfish Elimination Robotic Swarm), has been developed to cope with this problem. This paper presents formation control of JEROS and related experimental results through field tests. The JEROS is extended to multi-agent robot system and employs the leader-follower algorithm for formation control. The Theta* path planning algorithm is employed to generate an efficient path. Three prototypes of JEROS are implemented, and the feasibility of their formation control and the performance of jellyfish removal were demonstrated through field tests in Masan Bay located in the southern coast of South Korea.

Keywords: jellyfish removal, surface vehicle, navigation, path planning, formation control.

1 Introduction

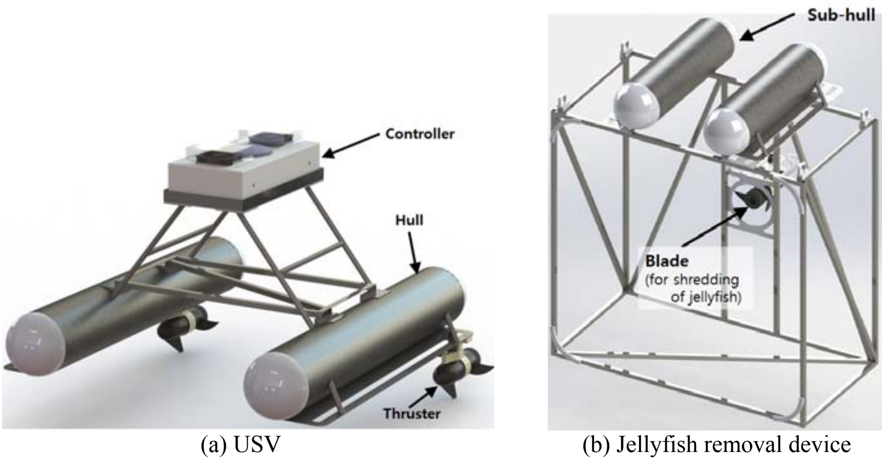
An enormous damage caused by proliferation of jellyfish has been reported in more than 14 countries around the world. The damage to fishery industries is the most serious, and seaside power plants and oceanic tourism are also damaged. The dominant causes of this problem are considered to be environmental pollution, global warming, destruction of the marine ecosystem, and an increased amount of marine structures. In South Korea, jellyfish population has steadily increased since 2000, and the damage to marine-related industries was estimated to be over 300 million USD a year in 2009 [1]. The most prevalent species of jellyfish along the coast of South Korea are *Aurelia aurita* and *Nemopilema nomurai* which have weak and strong venoms, respectively. In 2012, *Nemopilema nomurai* led a child to death in a beach in South Korea. In order to solve this problem, some studies have been carried out. The system consisting of two trawl boats equipped with jellyfish cutting nets has been developed [2, 3]. Utilizing large ships and many human operators, these systems have shown high performance in jellyfish removal, but it seems difficult to operate in narrow and shallow coastal areas. Other systems to prevent the influx of jellyfish into water intake pipes of power plants were developed. One of them used a camera and a water pump [4]; and the other system used a bubble generator and a conveyor device [5]. However, these systems are expensive to install and maintain.

In this paper, we introduce a multi-agent robot system for efficient jellyfish removal and field tests for formation control and jellyfish removal. An earlier version of autonomous jellyfish removal robot system, named JEROS (Jellyfish Elimination RObotic Swarm), was presented in [6-9]. The design of the ship, navigation and image processing algorithms, and feasibility tests for the algorithms and jellyfish removal were introduced. In this paper, its modified design, mainly in thrusters and communication methods, is presented. The robot system is extended to a multi-agent robot system composed of three prototypes of JEROS to enhance the efficiency of jellyfish removal, and the leader-follower scheme is employed to control formation of the multiple robots. Additionally, for the leader robot's autonomous navigation, the path planning algorithm based on Theta* path planning algorithm [10] and LoS (Line of Sight) guidance-based path following [11] method are embedded on JEROS. Finally, the feasibility of formation control and performance of jellyfish removal were demonstrated through field tests in Masan Bay located in the southern coast of South Korea.

In Section 2, the modified design of JEROS, the formation control based on the leader-follower scheme, and the Theta* algorithm-based path planning algorithm are described. In Section 3, experimental results of field tests for formation control and jellyfish removal are presented. Finally, in Section 4, we summarize this paper and discuss future works.

2 Formation Control and Path Planning of JEROS

2.1 Design of JEROS



(a) USV (b) Jellyfish removal device

Fig. 1. 3D CAD model of USV and device for jellyfish shredding.

The JEROS is made up of two parts. One is the USV (Unmanned Surface Vehicle) part and another is the part for jellyfish removal. The USV part needs to be designed for high payload, high stability, and high controllability. The twin-hull-type USV is more stable against waves than mono-hull-type, moreover it is easy to increase the payload using large hull and it is also easy to control just using two thrusters installed in the rear of two hulls. JEROS shreds jellyfishes using a blade and the jellyfishes are guided to the blade by a net shaped like a funnel. The 3D CAD design is shown in figure 1. The USV part can be operated alone with fastest speed and minimum power to perform the mission such as surveillance. To eliminate the jellyfishes, the removal part is assembled under the USV as shown in figure 2(a) and the prototype is implemented as shown in figure 2(b).

(a) JEROS (3D CAD model)

(b) JEROS assembled

Fig. 2. Overall system of JEROS.

Table 1. Electrical Parts of JEROS.

Device	Name	Manufacture
GPS	OEM Star	Novatel
IMU	EBIMU-9DOF	E2BOX
3G Modem	Snapdragon S3	Qualcomm
Zigbee Modem	EZBee-M100-EXT	Chipsen
Computer(SBC)	Core i7	Intel
Microprocessor	TMS320F2808	Texas Instrument
Thruster	Endura C2	Minnkota

The electrical control system is embedded in JEROS and its parts are listed in table 1. Sensors including GPS and IMU (Inertial Measurement Unit) are embedded in the system for localization. An SBC (Single Board Computer) and a microcontroller are embedded to process navigation and control algorithms. Two types of wireless communication modems for 3G mobile network and Zigbee are also embedded. The 3G modem is utilized to communicate with an external server computer, which allows JEROS to be operated at the place far from the external server computer. Additionally, Geographic Information System (GIS) map-based navigation algorithm is implemented using the 3G mobile network.

2.2 Formation Control

In order to enhance the efficiency of the jellyfish removal, JEROS is extended to a multi-agent robot system. The jellyfish removal task is performed by the motion of JEROS and shredding of jellyfish, and its efficiency depends on the area coverage rate and the performance of shredding. The area coverage rate is related to the water volume passed by the jellyfish removal device in a unit time, and it relies on the speed of JEROS and the dimensions of the jellyfish removal device. Its speed depends on thrust force. However, the dimensions of the jellyfish shredding device are hard to be enlarged, because the drag force increased by the enlarged device drops the speed of JEROS. Thus, JEROS is expanded to a multi-agent robot system and the leader-follower scheme for formation control is employed.

In the leader-follower scheme, one robot is assigned to be the leader and the others follow leader robot's motion with maintaining their formation. The leader robot follows desired path and determines the follower robots' motion. Each follower robot follows the waypoint calculated by using desired displacement and heading angle relative to the leader robot. A simple model of the leader-follower scheme is shown in figure 3.

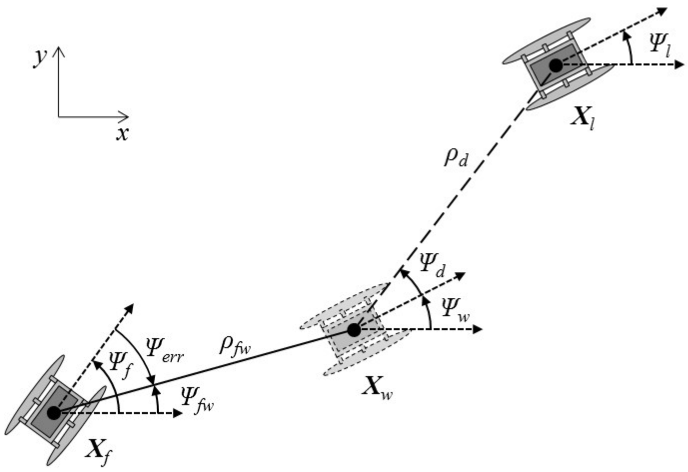


Fig. 3. A simple model of leader-follower formation control.

Let's consider a multi-agent robot system composed of n mobile robots, the position of each robot is described by $X_i = (x_i, y_i, \psi_i)^T$, where x_i, y_i, and $\psi_i \in [-\pi, \pi)$ describe x, y coordinates, and heading angle of the robot, respectively. The position of leader and follower robots are denoted by X_l and X_f, the waypoint which is the desired position of the follower robot is denoted by X_w, as shown in figure 3. X_w is determined by the desired displacement and heading angle, and is calculated as follows:

$$X_w = \begin{pmatrix} x_l - \rho_d \cos(\psi_d + \psi_w) \\ y_l - \rho_d \sin(\psi_d + \psi_w) \\ \psi_w \end{pmatrix} \tag{1}$$

where ρ_d and ψ_d denote the desired displacement and heading angle. Typically, ψ_w is same as ψ_l. The follower robot follows the waypoint using a guidance law and its desired and error heading angles are calculated as follows:

$$\begin{aligned} &\psi_{fw} = \tan^{-1}\left(\frac{y_w - y_f}{x_w - x_f}\right), -\pi \le \psi_{fw} < \pi \\ &\psi_{err} = \psi_{fw} - \psi_f \end{aligned} \tag{2}$$

where ψ_{fw} and ψ_{err} denote the desired and error angles in the guidance law. Its desired speed is determined to be proportional to the distance between the waypoint and the follower robot. Thus, the desired speed and heading angle of the follower robot can be controlled by two thrusters using the following equations [12]:

$$\begin{aligned} &\tau_d = K_p \rho_{fw} \\ &\tau_l = \begin{cases} \tau_d - \dfrac{\tau_d \cdot \psi_{err}}{K} & \psi_{err} > 0 \\ \tau_d & \psi_{err} \le 0 \end{cases} \\ &\tau_r = \begin{cases} \tau_d & \psi_{err} > 0 \\ \tau_d + \dfrac{\tau_d \cdot \psi_{err}}{K} & \psi_{err} \le 0 \end{cases} \end{aligned} \tag{3}$$

where τ_d, τ_l, and τ_r denote the central thrust force and thrust forces of the left and right thrusters, respectively, and K is a steering constant.

2.3 Path Planning and Following

The autonomous navigation technologies such as path planning and following are needed to approach an area where jellyfishes are densely populated. The LoS (Line-of-Sight) guidance algorithm is used to follow a generated path. The LoS guidance algorithm computes an LoS vector to calculate a desired heading angle. The LoS vector is formed by connecting the robot position to an intersecting point on the path at a distance of a tracking radius ahead of the robot [10]. To effectively follow a sequence of way-points by the LoS guidance algorithm, the way-points are created in the major inflection points. For the path planning, the Theta* algorithm was used. The

Theta* algorithm is very similar to A*. The difference between the algorithms is the method used to select a node. Theta* selects a node considering the line of sight [11]. The following algorithm 1 is the pseudo code of the Theta* algorithm.

Algorithm 1. Theta* algorithm.

1. Point_{start}.*Parentnode*←Point_{start}
2. *while found* Point_{goal} *do*
3. *for each* $\text{Point}_{neighbor}$ *do*
4. *if* lineofsight *then*
5. $\text{Point}_{neighbor}$.*Parentnode*←$\text{Point}_{current}$.*Parentnode*
6. *else* $\text{Point}_{neighbor}$.*Parentnode*←$\text{Point}_{current}$
7. *End*
8. *End*

As shown in figure 4, the Theta* algorithm takes localization and GIS data as inputs. The LoS guidance algorithm calculates the control input by using the Theta* results.

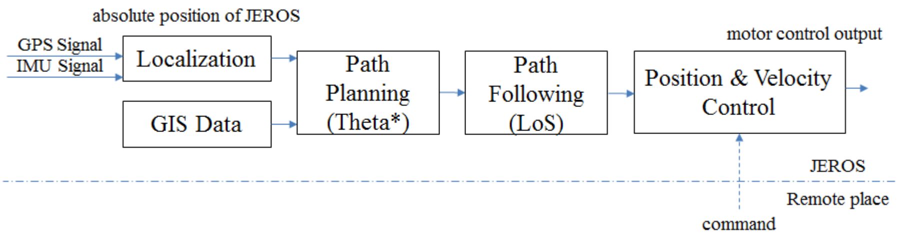


Fig. 4. Scheme of navigation and control system.

3 Experiments

3.1 Formation Control Tests

Field tests were carried out in Masan Bay located in the southern coast of South Korea to verify the feasibility of the proposed formation control. Our multi-agent robot system is composed of three JEROS prototypes. The leader robot follows a desired path generated by the Theta* algorithm and makes the overall motion of the robot system. Two follower robots receive absolute position of the leader robot through wireless communication (Zigbee) and follow the waypoint calculated by the absolute position. The desired displacement of both follower robots is set to 5.0 m and the desired heading angles of them are set to $\pi/2$ and $-\pi/2$, respectively. Results of the tests are shown in figure 5.

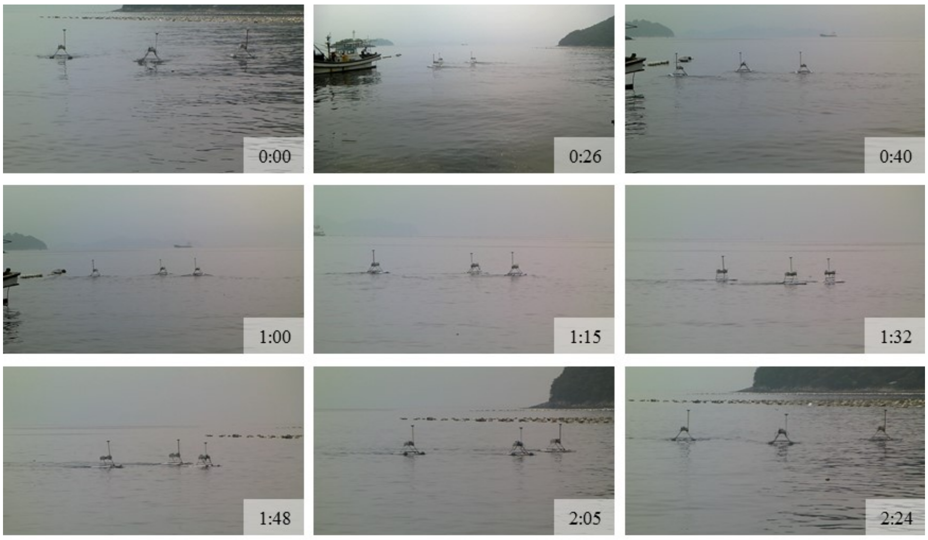


Fig. 5. A series of captured images while field tests. Caption indicate captured time (unit is min:sec).

3.2 Jellyfish Removal Tests

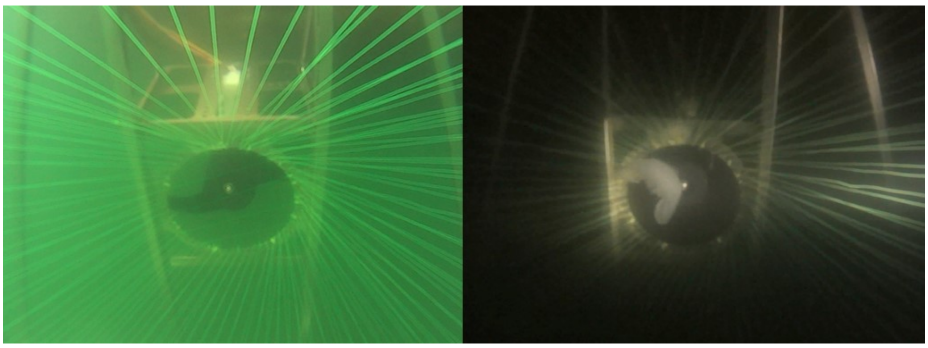


Fig. 6. Field tests for jellyfish removal: front view of the device for jellyfish removal (left) and a scene of jellyfish shredding (right).

The field tests to verify the performance of jellyfish removal were carried out in Masan Bay. The jellyfish were shredded by the device for jellyfish removal as shown in figure 6. Jellyfishes in front of the device were transferred to the blade going through the funnel-shaped net, and then they were pulled by thrust force and shredded by the rapidly rotating blade. The rate of jellyfish removal is proportional to the speed of JEROS, the area of entrance of jellyfish removal device, and the number of jellyfishes in unit volume. The speed of JEROS was about 0.5 m/s and the area of the entrance was 1.44 m^2. The tests were performed in a region where many jellyfish appeared. Jellyfish such as *Aurelia aurita* proliferates in the bay, because there are many docks, artificial seawalls, and farms. Additionally, the warm seawater temperature and the abundance of plankton have led to high populations of jellyfish in the bay. In the tests, 36 jellyfishes were removed for 1 minute on average.

4 Conclusion

In this paper, we presented the formation control of the autonomous jellyfish removal robot system, JEROS, and the field tests for formation control and jellyfish removal. To enhance the performance of jellyfish removal, the robot system was modified compared to the previous version with respect to its dimensions and thrust force; and it was extended to a multi-agent robot system composed of three prototypes of JEROS. For the autonomous navigation of the multi-agent robot system, the leader-follower scheme was employed to control its formation, and Theta* and LoS guidance algorithms were employed to path planning and path following, respectively. The feasibility of the formation control and the performance of the jellyfish removal were demonstrated through the field tests in Masan Bay. Future research will be focused on an advanced formation control algorithm and the investigation of the efficiency of the JEROS through various field tests.

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