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Development and Experimental Testing of an Autonomous Jellyfish Detection and Removal Robot System

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Abstract: The development of an autonomous jellyfish removal robot system, named JEROS, and related experimental results are presented in this paper. The number of jellyfish has drastically increased due to changes to the marine environment. Large jellyfish swarms are threatening marine ecosystems and inducing enormous damage globally to marine-related industries. JEROS has been designed based on a twin hull-type surface vehicle equipped with a device for shredding jellyfish. Additionally, an electrical control system, a guidance, navigation, and control (GNC) system, and a vision-based jellyfish detection system are embedded to remove jellyfish autonomously. The jellyfish removal mission starts when the location of jellyfish is detected, followed by planning a path for jellyfish removal, tracking the path using an autonomous navigation system, and shredding jellyfish while tracking. The performance of the vision-based jellyfish detection, navigation, and jellyfish removal was demonstrated through experiments in a pond and field tests in Masan Bay located on the southern coast of South Korea.

Keywords: Autonomous navigation, jellyfish removal, unmanned surface vehicle, vision processing.

1. INTRODUCTION

Jellyfish have increased largely in numbers since the late 1900s and have become a problem worldwide. Global concern about the destruction of the ocean ecosystem by their proliferation has increased, and damage to industries including fisheries, power plants, and oceanic tourism has been widely reported. The dominant causes of the increase in jellyfish are as follows: rise of ocean temperature due to global warming; provision of habitat for jellyfish polyps – the larval stage in the jellyfish life cycle [1] – due to an increased amount of marine structures; extinction of natural enemies due to overfishing of marine organisms; and increased food due to nutrient run-off from land [2–4]. The most prevalent species of jellyfish along the coast of South Korea are *Aurelia aurita* and *Nemopilema nomurai*, and they mainly appear during the season of high seawater temperature between May and September. They have caused large damage to marine-related industries, estimated at over 300 million USD a year in South Korea in 2009 [5]. The greatest damage has been reported in the fishery industries [6]. Such damage includes breakage of fishing nets due to the influx of a large amount of jellyfish, degradation of fish's salability caused by the tentacles of jellyfish, and injury to fishermen from jellyfish stings or broken tools. The jellyfish influx into the water intake pipes of seaside power plants has caused power generation stoppages and damage to filter facilities. In beach industries, the number of beach-goers that have been stung by poisonous jellyfish – which can lead to death in extreme cases – has risen.

Some studies on means of reducing the damage have been conducted. In the fishery industries, systems for jellyfish removal or separation have been developed. In Japan, a trawl net equipped with a jellyfish cutting device has been developed and tested on the nation's western coast [7]. Jellyfish cutting nets made of thin and hard wires were installed at the end of the trawl nets. The jellyfish removal tests using the trawler were successful and jellyfish were cut into small pieces less than 0.4 m $\times$ 0.4 m. The National Fisheries Research and Development Institute (NFRDI) in South Korea also developed a trawl net equipped with a triple jellyfish removal net [8]. The jellyfish removal performance of the trawl net was estimated as 1 ton per hour through tests on the southern coast of South Korea. NFRDI has also developed a jellyfish sep-

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aration and removal system that separates jellyfish from other fishes and removes the jellyfish using jellyfish cutting nets [9]. These systems have shown high performance of jellyfish removal using large ships and many human operators, but are difficult to operate in shallow coastal areas. In seaside power plants, some systems for removing jellyfish near the water intake pipes have been developed. Matsuura *et al*. [10] utilized a camera for vision-based jellyfish detection and a water pump to expel the detected jellyfish beyond a fence. Lee *et al*. [11] developed a system to prevent the influx of marine organisms into water intake pipes using a bubble generator and a conveyor device. The availability of this system depends on the geometry near the water intake pipes and effective jellyfish removal cannot be guaranteed in the case of large jellyfish influx.

Recently, robot systems are utilized for removing harmful underwater organisms, for environmental monitoring, and for inspection of underwater structures. Dunbabin *et al*. [12] surveyed field robotic systems for environmental monitoring focused on marine-based robot platforms and applications. They emphasized that the robotic systems play an important role in scientific data collection in a dangerous environment. Hover *et al*. [13] developed navigation and 3D mesh modeling algorithms for inspecting an underwater structure, such as a submerged ship hull, using an autonomous underwater vehicle (AUV). Jin *et al*. [14] and Loc *et al*. [15] developed AUV platforms for various marine applications. Hitz *et al*. [16] presented an autonomous surface vehicle (ASV) for the monitoring of inland water resources including the boom of noxious bacteria. Kitts *et al*. [17] developed a twin-hull type unmanned surface vehicle (USV) for bathymetric mapping in shallow waters. Kim *et al*. [18] proposed a path planning algorithm that generates a path for USV in consideration of both USV's heading angle and angular rate.

This paper proposes a novel jellyfish removal robot system, named JEROS (Jellyfish Elimination RObotic Swarm), that can be operated autonomously with less capital and manpower compared with the conventional systems. An earlier version of JEROS was presented by [19]. JEROS is designed as a twin-hull-type surface vehicle composed of a main body of a USV, a device for jellyfish removal, an electrical control system, an autonomous navigation system, and a vision-based jellyfish detection system with the purpose of removing jellyfish appearing within approximately 1 m under the sea surface. In this paper, the improved version of JEROS in terms of the design and implementation, and its experimental results are presented. Its buoyancy and payload are improved by scaling up the length and width of the USV, and its propulsive force is enhanced by increasing the power of the thrusters. The device for jellyfish removal is changed from jellyfish cutting grid to jellyfish shredding device. The autonomous navigation and vision-based jellyfish detection algorithms are also improved. Also, a strategy for jellyfish removal consisting of 3 steps is introduced. The strategy starts by generating a path to approach jellyfish when the location of jellyfish is inputted from an external server computer. In the next step, the robot system moves near the jellyfish along the generated path using the embedded autonomous navigation system. Finally, this system gathers and shreds the jellyfish while keeping track of the path.

In Section 2, the goals for system design and the strategy and hardware design for jellyfish removal are described. In addition, the entire operating system, the navigation system, and the vision-based jellyfish detection system for realizing the strategy are presented. In Section 3, experimental tests related to vision processing, navigation, and jellyfish removal using the prototype are described, and results of the tests are discussed. Finally, the last section summarizes this paper and presents directions for future work.

2. DESIGN AND IMPLEMENTATION OF JEROS

2.1. Design goals

Jellyfish have characteristics that distinguish them from other oceanic life. First, since jellyfish are composed of more than 95 % of water and a small amount of gelatinous material, they can be easily cut with a sharp instrument. Jellyfish consist largely of two parts: a gelatinous umbrella and tentacles. The umbrella can pulsate for locomotion, while tentacles sting enemies and eat plankton. For instance, the *Aurelia aurita* swims at a slow speed of lower than 10 cm/s by propulsion of its umbrella, whose size is around 15 cm in diameter, and it tends to move with the sea current [20]. Additionally, jellyfish such as *Aurelia aurita* and *Nemopilema nomurai* mainly appear during the summer season between May and September along the coast of South Korea. *Aurelia aurita* appears within a depth of around 1 m under the sea surface during summer daytime, because the jellyfish has a vertical movement and the depth of the jellyfish depends on the sea water temperature and plankton, and its vertical distribution is known to be from the sea surface to 15 m of water depth [21, 22]. Considering these characteristics, to accomplish the jellyfish removal mission successfully, the following design goals were set:

- device to eliminate jellyfish within a depth of 1 m under the sea surface
- jellyfish removal performance of 100 kg per hour
- vision-based jellyfish detection performance exceeding 90 % using a camera
- wireless data communication over 100 m distance to an external server computer
- autonomous navigation system
- operation time of more than 2 hours

2.2. Robot design

Following the design requirements, JEROS was designed as a twin-hull-type USV, as shown in Fig. 1. This USV is composed of two hulls, a body that houses the electrical control system, links that connect the hulls and body, two thrusters, and a device for jellyfish removal mounted underneath the USV. Since the two parallel hulls provide buoyancy, the USV is more stable against disturbances such as waves, current, and wind compared to mono-hull-type ships, and the ship is able to sustain its speed in rough head seas by its streamlined hulls [23]. Two thrusters are attached to the rear of the hulls. Thus, the heading angle is controlled by differential forces of the two thrusters. The earlier version of the USV was also designed as a twin-hull-type, but its buoyancy was not sufficient enough for required buoyancy aids and it was not so fast enough to go beyond high waves. Thus, the length and width of the USV are scaled up to 1.5 times of the earlier version to improve buoyancy and payload, and the power of the thrusters is doubled to enhance the propulsive force.

The device for jellyfish removal is designed to remove jellyfish appearing within 1 m under the sea surface and to be installed underneath the USV. The device was initially designed as a rectangular grid composed of a rectangular steel frame and a steel wire mesh, which cuts off jellyfish by passing the jellyfish through the mesh quickly using the propulsive force of the USV. However, the performance of jellyfish removal was poor, because it was difficult to generate enough propulsive force to cut off jellyfish. The reason for the poor propulsive force is that the drag force induced by the grid is high and the drag force is increased when the jellyfish which have not been cut off are stuck in the grid. Thus, the device is required to induce low drag force, to prevent jellyfish from being stuck in it, and to cut off jellyfish with low propulsive force. Finally, the device is redesigned to shred jellyfish by attaching a rectangular funnel shaped net and three blade-equipped underwater motors, as shown in Fig. 1. The jellyfish entering the device's wide inlet are transferred smoothly along the funnel shaped net to the narrower outlet by the propulsive force of the robot, and are then suctioned and shredded by the three rapidly-rotating blades installed at the end of the net.

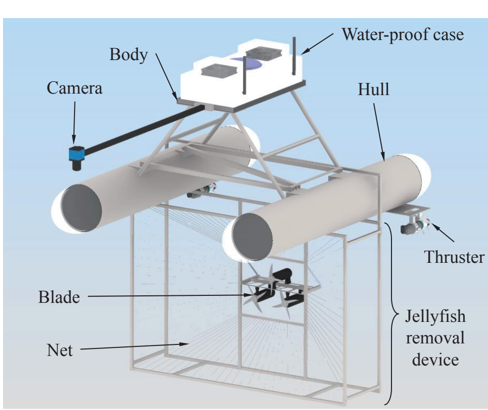


Fig. 1. Rendered image from 3D computer-aided design (CAD) model.

2.3. Electrical control system

The brain of JEROS is the electrical control system, which is composed of a main control system embedded on JEROS and a remote control system located at a remote place, as shown in Fig. 2. The main control system consists of sensors, processors, and drivers and has been embedded on the top of JEROS in a water-proof case equipped with cooling fans. To prevent the influx of water through the fans, each cooling fan has been covered with a plastic cap and the case is installed on a 0.8 m from sea surface. The plastic cap is designed with three layers of partitions and several holes to stall the water between the layers and drain off the water, respectively. The sensor parts consist of a commercial color CCD camera, GPS, and an IMU. The camera installed at the front of JEROS, as illustrated in Fig. 1, is used to detect jellyfish under the sea surface. GPS provides location information with 1.5 m accuracy [24] and the IMU provides attitude information with respect to the earth coordinate system. A single board computer (SBC) and a microprocessor have been included to process a variety of algorithms and to control JEROS. The SBC based on a 2.0 GHz Intel Centrino Mobile Dual Core CPU acquires data from the sensors and processes the navigation and control algorithms, and the microprocessor drives the thrusters and the blade-equipped motors. Power is provided by two types of Lithium-Polymer (Li-Po) battery packs, generating 22.2 V with a capacity of 33.2 Ah for driving the thrusters and the blade-equipped motors, and 14.8 V with a capacity of 16.2 Ah for other parts of the system, respectively. Detailed information on the electrical parts is listed in Table 1. The detailed specifications of the prototype are described in Section 3.

A remote control system including an external server computer is placed at a remote location. Being connected to the SBC through Wi-Fi and ZigBee wireless communications, this server computer plays roles of both monitoring all states of JEROS and commanding JEROS to start

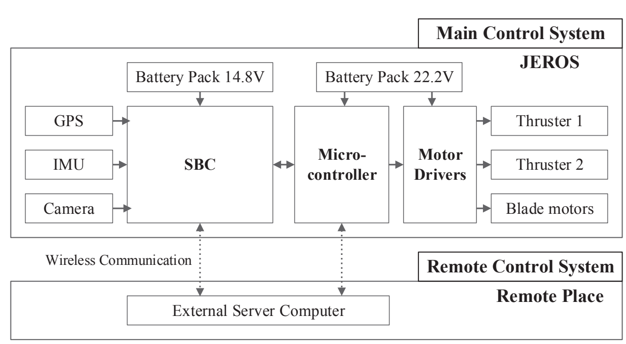


Fig. 2. Block diagram describing electrical control system.

Table 1. Electrical parts of JEROS.

Device	Name	Manufacturer
Camera	DFK 31AU03	Imaging Source
GPS	OEMV-1	Novatel
IMU	EBIMU-9DOF	E2BOX
SBC	Core 2 Duo	Intel
Microprocessor	TMS320F2808	Texas Instruments
Thruster	Model-300	Tecnadyne
Blade Motor	BTD150	Seabotix
Battery	Li-Po 14.8/22.2 V	PolyQuest

the jellyfish removal mission by transmitting the location of jellyfish. Additionally, JEROS can be manually controlled in case of an emergency or a mission failure.

2.4. GNC system

The GNC (Guidance, Navigation, and Control) system is composed of a localization module, a vision processing module, a path planning module, a position and velocity control module, and a monitoring module. These modules are processed on a SBC, a microcontroller, and an external server computer. The architecture of the system is illustrated in Fig. 3. The localization module estimates the current position and heading angle of JEROS using GPS and IMU, respectively. The location of jellyfish transmitted from the external server computer, is used to generate a path for jellyfish removal in the path planning module. The generated path is followed using an inertial navigation algorithm including a guidance algorithm in the position and velocity control module, as described in detail in Section 2.5. The vision processing module detects jellyfish through a camera and commands the jellyfish shredding device to run when the jellyfish is detected. The monitoring module was implemented to observe the status of JEROS at a remote place through wireless communication. While monitoring, manual control is also available by transmitting simple control commands or desired path

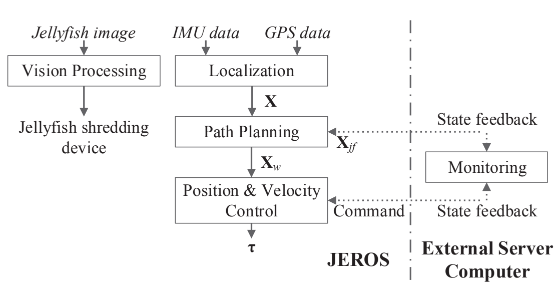


Fig. 3. Block diagram describing the architecture of the overall system. $\mathbf{X}_{jf}$ is the position of jellyfish, $\mathbf{X}_w$ is a vector that contains a sequence of way-points, τ is defined as a vector of desired thrust force for two thrusters, and $\mathbf{X}$ denotes the current location and heading angle of JEROS.

information to JEROS.

2.5. Autonomous navigation

The jellyfish removal mission is composed of autonomous navigation and jellyfish shredding. When the rough position of jellyfish is reported, the mission begins and the robot autonomously navigates until it arrives at the destination. On arrival, the robot covers the region around the position of jellyfish while following a zigzag path and shredding jellyfish, and then it returns to the starting position. In order to perform the jellyfish removal mission successfully, the autonomous navigation system is important, and the system was designed with this consideration as shown in Fig. 4. It consists of a localization module, a path planning module, and a position and velocity control module.

The navigation system starts when a region of a jellyfish swarm is transmitted from an external server computer. The jellyfish information for this server computer can be offered by a jellyfish monitoring center such as the jellyfish task force team of NFRDI [26]. The jellyfish task force team analyzes data of the emergence and the number of jellyfish in all coast area of South Korea, which is gathered by jellyfish monitoring agents including fishermen. The organized data is periodically reported in their website (http://www.nfrdi.re.kr/bbs?id=jellynews). Once a region of jellyfish is identified, a zigzag path to cover the region is generated as a sequence of way-points in addition to the path for approaching to the region. The generated path is followed asymptotically using the line-of-sight (LOS) guidance algorithm introduced by [27]. Fig. 5 shows the LOS guidance algorithm that generates a heading angle for heading control by computing an LOS vector, which is formed by connecting the robot position to the next way-point or an intersecting point on the path at a distance of R ahead of the robot. The desired heading angle can be calculated as:

$$\Psi_d = \tan^{-1}\left(\frac{y_{los} - y}{x_{los} - x}\right), -\pi < \Psi_d \leq \pi. \tag{1}$$

While tracking the path, the way-point is switched to the next way-point when the robot approaches within a circle of acceptance (COA) with a radius R_0 around the way-point. A tracking error is defined as a cross-track error, which is the shortest distance between JEROS and the

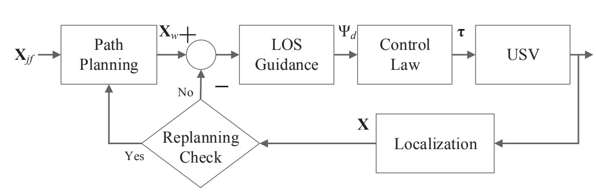


Fig. 4. Block diagram describing the architecture of the navigation system. Ψ_d denotes the desired heading angle.

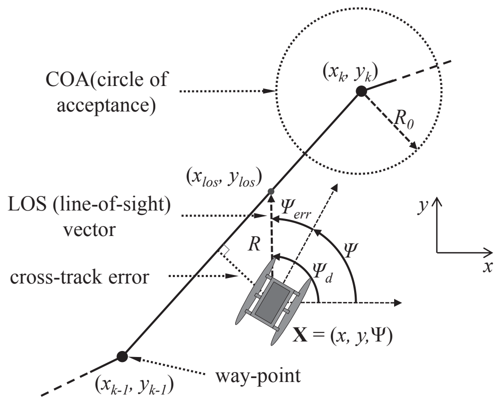


Fig. 5. Path following using LOS guidance law. The LOS point (x_{los},y_{los}), way-points (x_k, y_k) and (x_{k-1}, y_{k-1}) are marked on the path. The LOS vector that has a length of R is defined by a vector from the robot position to the LOS point. The error of the heading angle, Ψ_{err}, with respect to the earth frame for generating thrust forces can be calculated by the difference between Ψ and Ψ_d. COA with a radius R_0 lies on the next way-point. Cross-track error is defined by the shortest distance from JEROS to the desired path.

desired path.

A large R is adequate for smooth guidance and a small R is needed for precise guidance. However, an excessively large R could result in intolerably large cross-track errors and an overly small R could cause frequent fluctuation of the desired heading angle, thereby making it difficult for JEROS to follow a path [28]. R_0 has similar characteristics to R around the way-points.

The velocity and heading angle of JEROS are controlled by two thrusters in the microprocessor using the following equations [29]:

$$\tau_l = \begin{cases} \tau_d - \frac{\tau_d \cdot \Psi_{err}}{K} & \Psi_{err} > 0 \\ \tau_d & \Psi_{err} \leq 0 \end{cases}$$
$$\tau_r = \begin{cases} \tau_d & \Psi_{err} > 0 \\ \tau_d + \frac{\tau_d \cdot \Psi_{err}}{K} & \Psi_{err} \leq 0 \end{cases}, \quad (2)$$

where τ_d, τ_l, and τ_r denote the central thrust force and thrust forces of the left and right thrusters, respectively; Ψ_{err} is the difference between the desired and current heading angles; K is a steering constant. If JEROS follows a straight path with a very small value of R or K, the robot might frequently fail to follow the path or might not converge to the path. Finally, the jellyfish are removed by the jellyfish shredding device. When the jellyfish in front of JEROS is detected in the vision processing module, the blade motors of device are activated and the removal process begins. The removal process is explained in detail in Section 3.3. If the battery level drops under a specific threshold while performing the jellyfish removal mission, the robot autonomously returns to the start point.

2.6. Image processing for jellyfish detection

Most of the related studies on the detection of jellyfish based on a vision system have focused on surveying the underwater environment. Numerous detection algorithms have accordingly been introduced for the marine environment. Rife *et al*. [30] introduced a method for segmentation and tracking of jellyfish using underwater images. The segmentation processes including various filters separate candidate regions of jellyfish from the background based on gradient operations, and the jellyfish regions recognized by a human operator are tracked based on optical flow. In the present research, however, since the USV-type robot is designed, the jellyfish detection algorithm detects the jellyfish just below the surface of the water using a down-looking camera, and a cascade of classifiers are employed to automatically detect jellyfish regions. One commercial CCD camera connected to the SBC is used for the vision system. The framework proposed by Rife *et al*. [30] was modified to build the proposed algorithm. In order to detect jellyfish autonomously, filters for noise reduction and a cascade of classifiers are employed. In the filtering process, the noise reduction algorithm [30] is employed, and an algorithm to extract dark regions is newly designed to remove outlier candidates of dark regions generated by the rolling of sea waves. These filters are helpful for improving the detection rate of jellyfish. Whereas the framework of [30] needs a human to select jellyfish among the filtered regions, the proposed algorithm includes the cascade of classifiers to automatically determine whether each filtered region is a jellyfish in the classification phase as shown in Fig. 6.

The jellyfish detection algorithm is performed at every processing step based on the sea surface image obtained from a camera sensor. The algorithm consists of two phases, filtering and classification, as illustrated in Fig. 6. First, in the filtering phase, as illustrated in Fig. 6(a), the input image (Fig. 7(a)) is converted into a gray as shown in Fig. 7(b), after a noise reduction and a smoothing operation is performed such as a meanshift filter [31] or bilateral filter [32]. The outlines of objects are then detected by applying a morphological gradient operation, as shown in Fig. 7(c). However, dark regions may appear due to the rolling of sea waves, which impedes extraction of the edge of jellyfish. In order to solve this problem, after detecting the dark areas in the original image, erosion and morphological gradient operations are applied to the areas sequentially. The processed dark areas, as shown in Fig. 7(d), are then removed from the original image. Finally, blob labeling is performed and the candidates of jellyfish are detected. These filtering processes were applied to real jellyfish images on the surface of the ocean, and the results are shown in Fig. 7(e).

In the second phase, as shown in Fig. 6(b), the selected candidates are classified and the regions of jellyfish are de-

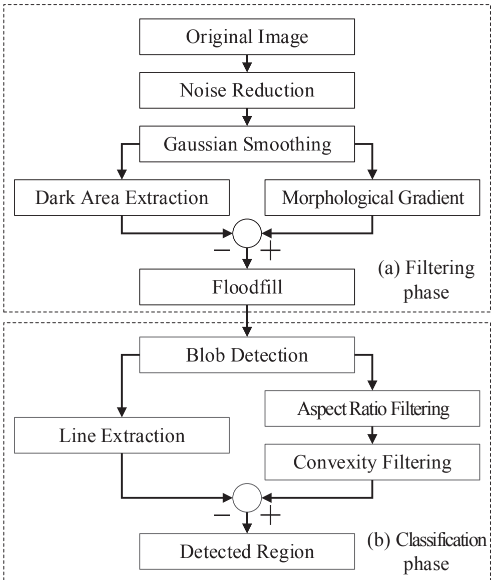


Fig. 6. Block diagram describing the sequence of image processing for jellyfish detection.

tected. In order to classify jellyfish, outlier blobs among the candidates are excluded according to three characteristics of other inlier blobs: the jellyfish projected on the image plane is a round shape, the jellyfish usually has an aspect ratio of between 0.25 and 4, and the outlines of the other regions usually consist of line components. This process was applied to actual jellyfish images and videos, and the final detection result is illustrated in Fig. 7(f).

3. EXPERIMENTAL RESULTS

Experimental tests have been performed with a JEROS prototype composed of a USV and a jellyfish shredding device, as shown in Fig. 8. The USV has dimensions of 1.5 m $\times$ 1.1 m $\times$ 0.8 m (length $\times$ width $\times$ height) and a weight of about 50 kg in air; the jellyfish shredding device has dimensions of 0.3 m $\times$ 1.1 m $\times$ 1.0 m (length $\times$ width $\times$ height) and a weight of about 5 kg in air. The average speed of the USV is about 1.0 m/s while following a path, and when the jellyfish removal deviceis attached to JEROS, it runs at average speed of about 0.5 m/s. The batteries for operating two thrusters and blade-equipped motors have the power of 737.04 Wh. The maximum power consumption of the thrusters and motors is 600 W and 450 W, respectively. However, while performing a mission, since the thrust forces of the thrusters are controlled and the motors are activated when the inflow of jellyfish is detected, we assumed that the average power consumption is about 300 W (50 % of the maximum power consumption) and 67.5 W (15 % of the maximum power consumption), respectively. Thus, the batteries provide enough power to run the JEROS without the jellyfish removal device at average speed of 1.0 m/s

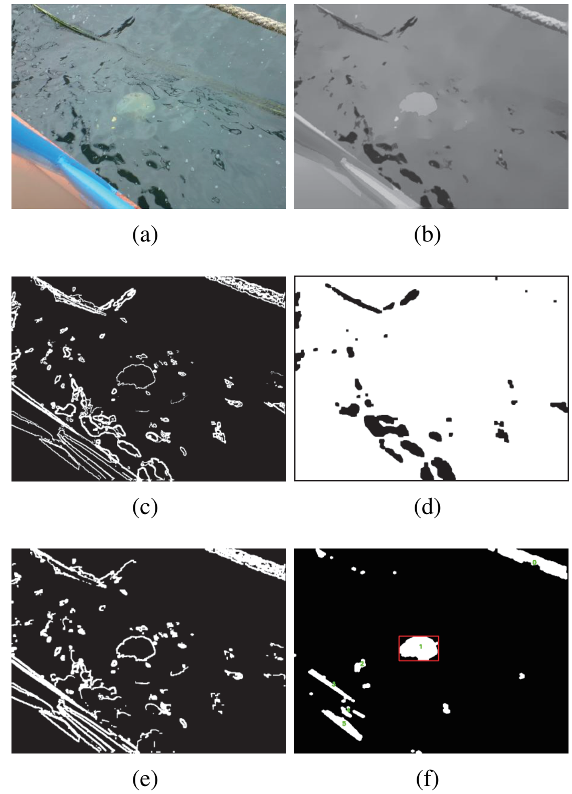


Fig. 7. Image processing results of a real jellyfish image. (a) Input image, (b) gray scale image after noise reduction filtering, (c) result of the morphological gradient operation, (d) extracted dark areas, (e) result of subtracting dark areas from (c), (f) result of blob labeling, classification, and jellyfish detection.

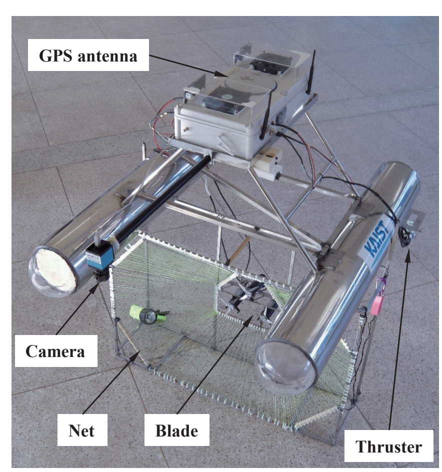


Fig. 8. Photograph of a prototype of the autonomous jellyfish removal robot system, JEROS.

for about 2.5 hours. When the jellyfish removal device is installed underneath the USV, the operating time is estimated to be about 2 hours and the average speed is about 0.5 m/s. The allowable operation condition of JEROS is

(a) 0/789 (b) 301/789 (c) 591/789 (d) 786/789

Fig. 9. Jellyfish detection results from real jellyfish video. Each caption below the figure shows the frame number among the total number of frames.

sea state 2 and the field tests were carried out in that condition[1]. The prototype is connected to an external server computer through wireless communication via Wi-Fi and ZigBee, which allow communication over a distance of 10 m and 100 m, respectively. Wi-Fi is used to inspect and to initialize the GNC system prior to performing a mission, and ZigBee is used to transmit control commands and to monitor all states of JEROS during the mission. Thus, Wi-Fi and ZigBee provide sufficient communication ranges for JEROS. The tests were carried out during the summer season from June to August 2012 in a pond at KAIST and at Masan Bay located on the southern coast of South Korea. The aims of the tests were to validate the performance of vision-based jellyfish detection and navigation and to prove the practical validity of the jellyfish removal method.

3.1. Vision-based jellyfish detection tests

Experiments were carried out to validate the performance of the vision-based jellyfish detection algorithm described in Section 2.6, where a video clip was taken with a resolution of 800×480 pixels at 30 fps. 789 frames of the video clip contain *Aurelia aurita* floating on the sea surface of Masan Bay. However, when the direct rays of the sun are projected on the sea surface, jellyfish are not visible through the camera, as is also the case with the naked eye. The video clip was thus taken while keeping the direction of the camera perpendicular to the sea surface. The camera has the field of view (FOV) of about 90° and is mounted at the height of 0.6 m from the sea surface, which allows the jellyfish detection range of about 1.0 m in diameter.

In order to evaluate the performance, TPR (True Positive Rate) and FPR (False Positive Rate) have been used for the performance evaluation metrics [33]. TPR, or sensitivity, represents the ratio of true positives (TP) to actual trues (TPR=TP/(TP+FN)). FN stands for false negative, and FPR can be calculated as FP/(FP+TN) where FP and TN denote false positive and true negative, respectively. TPR is the proportion of correct detection of jellyfish that yield positive test outcomes. FPR is the rate

Table 2. Results of jellyfish detection.

Evaluation metrics	Conventional	Proposed
TP	1,117	1,282
FN	178	13
FP	0	0
TN	283	283
TPR	0.86	0.99
FPR	0.00	0.00

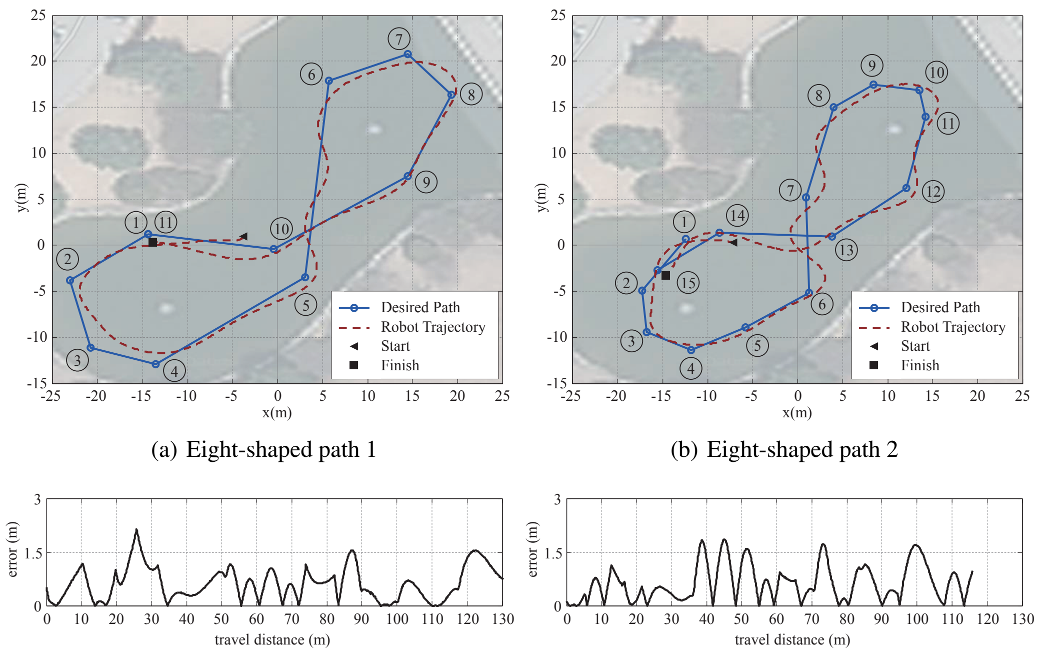
of absent detection events that also yield positive test outcomes. Larger TPR and smaller FPR are desirable.

The jellyfish detection algorithm is evaluated using the video clip and compared with the results of the conventional algorithm proposed by [30]. The filtering phase of the conventional algorithm was implemented by referring to the method introduced by [30], and the proposed classification phase was used to recognize jellyfish. In Fig. 9, the detected jellyfish are marked by solid boxes in each frame. The results are summarized in Table 2. The results show that there are no incorrectly recognized cases in the two experiments, and erroneously detected cases are reduced by 92.7 % in our approach compared with the conventional approach. Thus good detection results with a TPR of 0.99 and a FPR of 0.00 were obtained with the proposed method.

3.2. Navigation tests

Feasibility tests of the navigation system including path planning and guidance algorithms were performed through outdoor experiments at a pond in KAIST (Korea Advanced Institute of Science and Technology). Since the path planning and tracking are very important to successfully perform the jellyfish removal mission, their performance was demonstrated. In the tests, the jellyfish removal device was excluded from the robot system to measure the sole performance of the USV's navigation. The parameters of the LOS guidance algorithm such as the length of the LOS vector and the radius of the COA were equally set to 3 m (2 times the boat length). The size of the pond is about 1,200 m^2, and there are two fixed obstacles, as shown in Fig. 10. The desired path is manually set to an eight-shaped closed path, and the path and its way-points are

[1]Sea state 2 is the condition of smooth wave of which height is from 0.1 to 0.5 m [25].



(a) Eight-shaped path 1

(b) Eight-shaped path 2

(c) Path-tracking errors (path 1)

(d) Path-tracking errors (path 2)

Fig. 10. Results of path tracking tests at a pond in KAIST.

indicated by solid lines and circular marks in the figure, respectively. The prototype system autonomously navigated following the path at an average speed of 1 m/s, and the dashed curves on the figure show trajectories of JEROS measured by GPS. The GPS embedded in JEROS, Novatel OEM-V1, provides absolute location information with 1.5 m of accuracy at 10 Hz.

Cross-track errors from the eight-shaped paths 1 and 2 are plotted in Fig. 10 (c) and (d). The maximum absolute error of the first test is 2.15 m around the third way-point; however, except for the peak, the overall error is less than 1.6 m (about half of the length of the LOS vector). The second test shows maximum absolute error of 1.86 m. An overshoot occurs at the interval between the sixth and eighth way-points beginning at the end of the straight motion of the fourth to sixth way-points, and the overshoot thereafter is reduced gradually. These results indicate that the LOS guidance algorithm-based navigation is sufficient to operate JEROS for jellyfish removal. When JEROS is operated in the ocean, wind and waves can be dealt with by adjusting the parameters of the LOS guidance algorithm such as R and R_0 appropriately. Small parameter values allow precise guidance, but can lead to failure in path-following and frequent re-planning of the path [28]. Smooth guidance with large parameter values provides robustness to disturbances.

3.3. Jellyfish removal performance

The field tests for jellyfish removal were carried out two times in Masan Bay located on the southern coast of South Korea during August 2012. Since there are many piers, artificial seawalls, and farms in the bay, jellyfish such as *Aurelia aurita* proliferate in this area. Additionally, the high seawater temperature and the abundance of plankton have led to high populations of jellyfish in the bay. The performance of jellyfish removal was tested by manually driving the robot in the ocean environment. The tests were performed at around 3 p.m. in a region where many jellyfish appeared and no obstacles were found. The jellyfish were removed as shown in Fig. 10 using the device for jellyfish removal described in Section 2.2. Jellyfish moving in front of the device were pulled and shredded by the rapidly rotating blades.

Table 3. Results of jellyfish removal.

Experiment	Number of removed jellyfishes
1	81 for 3 minutes
2	20 for 1 minute

The number of shredded jellyfish was measured by analyzing underwater video clips taken by an underwater camera while JEROS was performing a jellyfish removal mission at an average speed of 0.5 m/s. The results are listed in Table 3. Experiment 1 shows 81 removed jellyfish for 3 minutes, and experiment 2 shows 20 removed jellyfish for 1 minute. Therefore, we can estimate removal performance of about 25 jellyfish per minute. In addition, assuming that the average weight of jellyfish is about 0.1 kg [34], removal performance of about 150 kg per hour is predicted.

4. CONCLUSIONS

This paper presented a novel autonomous robot system, JEROS, to reduce damage to marine-related industries by harmful jellyfish. Since harmful jellyfish such as *Aurelia aurita* float just below the sea water surface when the temperature of the sea water is high, JEROS was designed based on a twin-hull-type USV equipped with a device for gathering and cutting off jellyfish composed of a net and rotating blades. An electrical control system for autonomous navigation, and a strategy for jellyfish removal were also presented. The strategy consists of planning a path via which the robot will pass through jellyfish swarms; tracking the path by using the navigation system; and shredding jellyfish. The feasibility of this robot system was demonstrated through field tests performed on *Aurelia aurita* along the southern coast of South Korea. The proposed vision-based jellyfish detection algorithm consisting of filtering and classification phases showed a detection rate of more than 99 % in the experiment. The performance of the navigation system was tested through experiments in a pond, which showed sufficient path tracking performance. Finally, the performance of jellyfish removal was measured to be about 25 jellyfish per minute through field tests, corresponding to about 150 kg per hour.

For further study, we are concentrating on enhancement of jellyfish removal performance. It is obvious that this performance depends on the speed of JEROS, the throughput of the device for gathering and shredding jellyfish, and the density of jellyfish below the sea surface. The cruising speed and the throughput of jellyfish removal will be enhanced by revising the boat and the shredding device. We are planning to expand this robot system to a multi-agent cooperative robot system by making additional robot platforms and by applying formation control for a robotic swarm, which will greatly enhance the efficiency of the jellyfish removal. Performance of over 1 ton per hour in the future is targeted using the cooperative multi-robot system. Furthermore, the jellyfish detection algorithm will be improved through field tests in diverse environments and extended to detect jellyfish using an underwater camera.

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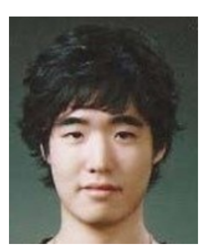

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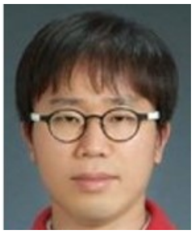

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