Development of an Unmanned Surface Vehicle for Harmful Algae Removal

Wonse Jo[1], Jee-Hwan Park[1,2], Yuta Hoashi[1,2], and Byung-Cheol Min[1]

Abstract— **In this paper, we introduce a small and low-cost unmanned surface vehicle (USV), the *SMARTBoat 5*, capable of removing harmful algal blooms (HABs), which are a rising environmental issue worldwide. The developed USV is a hovercraft type, operated by two propellers with duct fans; it is able to freely move even in shallow water and to approach shorelines. For eco-friendly, immediate, and safe control of algae, the USV is equipped with a novel water suction mechanism that enables it to actively collect algae without physical contact. In addition, it is equipped with a mesh net-based algae filter system that is easily disassembled and replaced. The USV system is supported by the Robot Operating System (ROS) for expandability and use in diverse applications. The performance of the proposed water suction mechanism and USV platform overall are validated through computational fluid simulation (CFD) and experiments in both lab and real environments.**

Index Terms— **Harmful Algae Blooms, Unmanned Surface Vehicles, Computational Fluid Simulation, Robot Operating Systems, Successive Linear Programming**

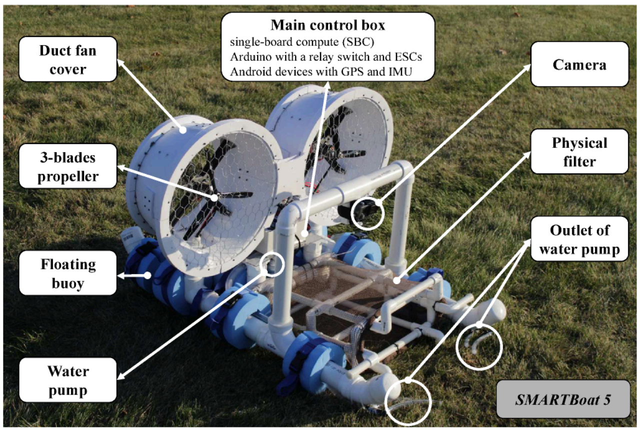

Fig. 1: Developed USV platform for harmful algae removal, called *SMARTBoat 5*.

I. Introduction

In recent years, water resources have been progressively subject to eutrophication or excess nutrients (nitrogen and phosphorus) due to increases in pollutant sources (e.g., sewage dumping and agricultural runoff) and to the rise in temperature from climate change; this has led to increased incidence of harmful algal blooms (HABs) and a gradual expansion of the range they affect [1], [2]. HABs are initiated in the transition region between coastal and offshore waters by the availability of rich nutrients, and then expand into the middle of the water resource [3]. The algae tends to be easily decomposed by microbes, which consumes dissolved oxygen; combined with the tendency of the expanded algae bloom to block sunlight, this causes a deficit of oxygen and results in deterioration of water quality [4]. Furthermore, HABs cause considerable expenditures and economic losses for human society [5], such as lost tourism revenue and polluted drinking water, injuries to human health (e.g., rashes, skin, and eye irritation), water odor, and so on [6].

Although HABs are detrimental to both the ecosystem and human society, they also play an essential role in aquatic ecosystems, including supplying nutrients to plants and animals [7]. Thus, algae should not be eradicated but to prevent environmental pollution while providing the proper amount to the aquatic food web. Accordingly, various methods have recently emerged for the control of algae growth and the effective resolution of the environmental issues posed by HABs.

Sengco et al. [8] proposed to disperse clay over the water surface to remove algal cells. The clay particles induced condensation with the algal cells, and the aggregated mass of clay and algae then sank to the bottom of the sea. Turker et al. [9] presented an organism-based method of algae removal. They showed that stocking lakes with fish (Nile tilapia) and then discharging the fish was effective in reducing the algae percentage. Ma and Liu [10] presented a chemical method using potassium ferrate that accelerated coagulation, allowing the easy gathering of algae cells. Wu et al. [11] and Heng et al. [12] introduced ultrasonic treatments to control HABs in lakes. They showed their methods were able to effectively inactivate algal cells and remove algal toxin.

Several mechanical methods for removing HABs have utilized conveyor belts in the algae removal process. Myers and Hayes [13] and Vasby [14] presented an aquatic weed harvester that uses a propeller paddle to move around and collect algae. The algae is scraped them off using a toothed plate in the front, and then carried back using the conveyor belt. Jung et al. [15] proposed a multi-robot team consisting of an unmanned surface vehicle (USV) and an unmanned aerial vehicle (UAV). The USV uses a novel electronic device to coagulate the algal cells, and removes HABs from the large environments.

However, these methods are expensive and have the potential to negatively affect aquatic ecosystems. Also, the platforms are too large and heavy to be practical in situations common to small water resources (such as ponds and lakes), and they face difficulties in approaching shorelines with

[1]All authors are with the SMART Lab, Department of Computer and Information Technology, Purdue University, West Lafayette, IN 47907, United States {jow,park458,yhoashi,minb}@purdue.edu

[2]J. Park and Y. Hoashi are with the School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, United States.

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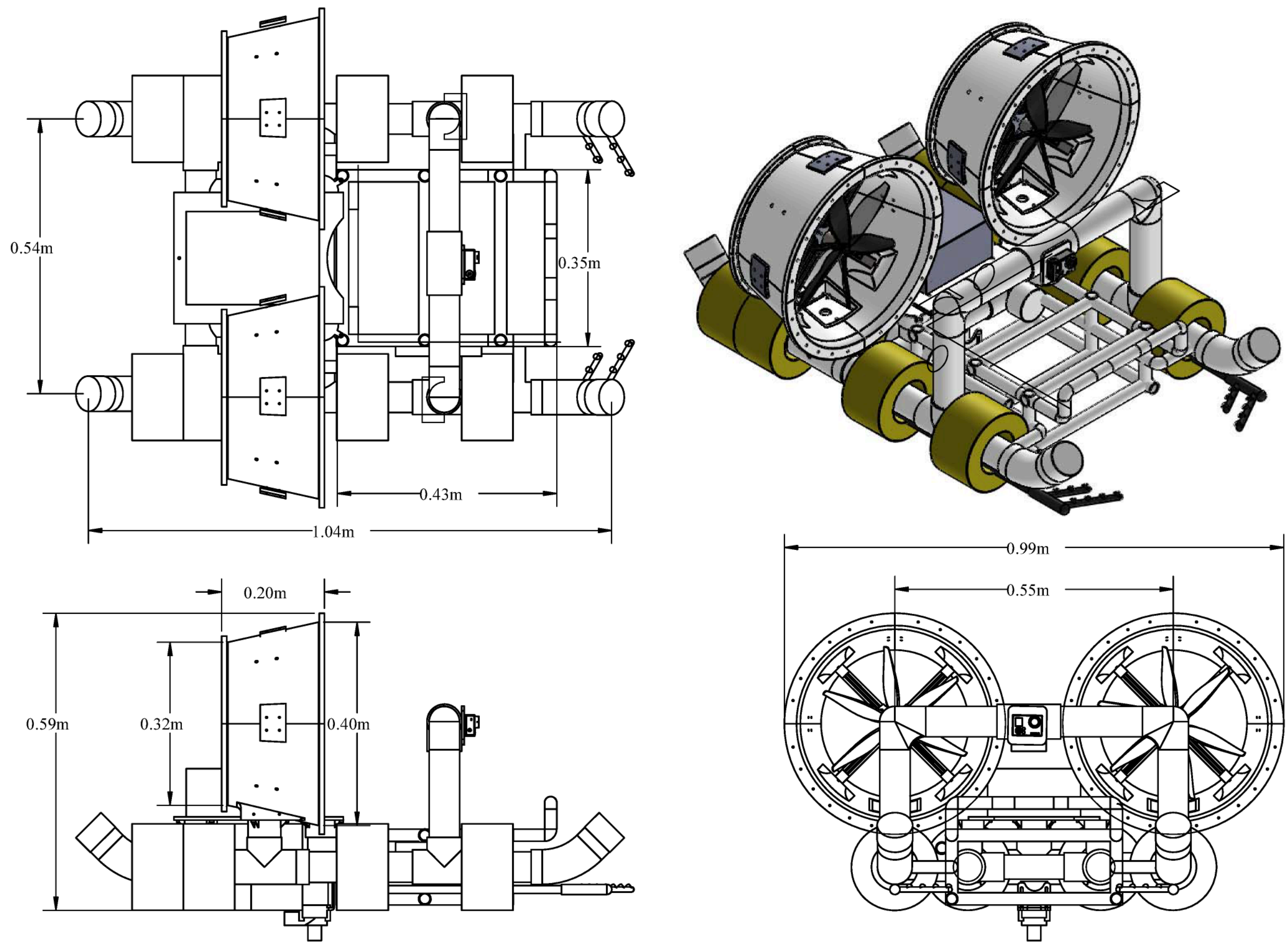


Fig. 2: Detail drawing of the *SMARTBoat 5*. The hardware dimensions are $1.04\,\mathrm{m} \times 0.99\,\mathrm{m} \times 0.59\,\mathrm{m}$ (L×W×H), and the mass is about $15\,\mathrm{kg}$.

shallow waters, surrounded by bushes, or that have irregular terrain. Therefore, we introduce a hovercraft type and eco-friendly USV platform for algae removal based on a water suction mechanism whose action is immediate and that can safely control HABs without ecosystem disruption.

This paper is organized as follows: In Section II, we provide a detail of the hardware and software of the developed USV. In Section III, we present the experimental procedure and results of the proposed water suction mechanism test and mobility and usability tests of the USV platform in both lab and real environments. We conclude the paper and discuss future work in Section IV.

II. USV Platform for Algae Removal

A. Hardware System

Fig. 1 illustrates the USV platform, and Fig. 2 shows its detail drawing presented in this paper, called *SMARTBoat 5*, which can be used in a variety of environments ranging from small and shallow ponds to large lakes. The platform is a hovercraft type operated by dual three-blade propellers ($12''$ diameter and $8''$ pitch) with duct fan covers. This hovercraft type was adopted to prevent the underwater thrusters from destroying the aquatic ecosystem and to allow the USV easily approach the shoreline without tangling with seaside plants. The hardware dimensions are $1.04\,\mathrm{m} \times 0.99\,\mathrm{m} \times 0.59\,\mathrm{m}$ (L×W×H), and the mass is about $15\,\mathrm{kg}$ which allows human operators to easily carry and quickly dispatch the platform. Its maximum speed is approximately $0.2\,\mathrm{m/s}$. The body frame was designed with 3D printed parts, floating buoy, and PVC pipes to increase the buoyant force, and every connection was sealed with waterproof tape to prevent water from entering the pipes. Also, the USV has a mesh netting based filter system (i.e., algae collector) at the center of the platform. The maximum carrying capacity is $0.033\,\mathrm{m}^3$. The filter system was designed to be easily disassembled or replaced when needed (e.g., when the filter full of the HABs); the procedure presents in Fig. 7d. The total cost of the developed platform is approximately 500 USD that is much cheaper than the commercial and other USV platforms and HABs removal methods [16].

To produce an eco-friendly USV platform, we developed a water suction mechanism that effectively collects algae by creating an artificial water current on the water surface (a blue arrow in Fig. 5a); the attached pump sucks up water

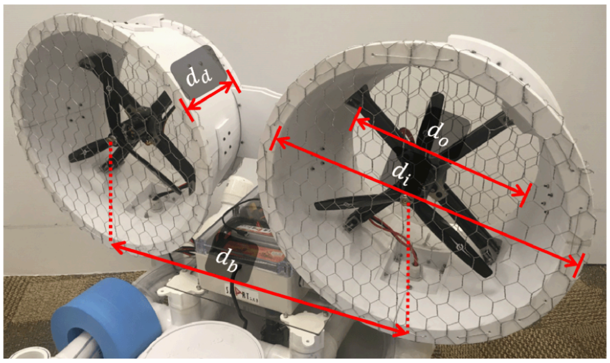
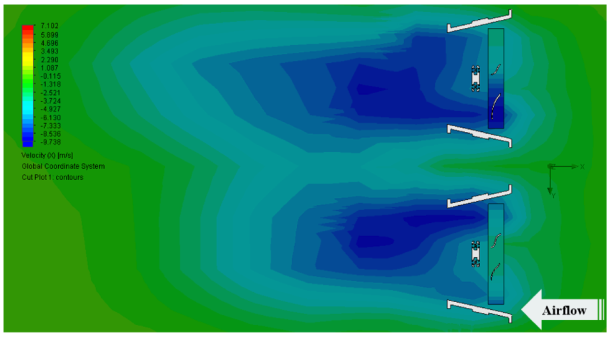
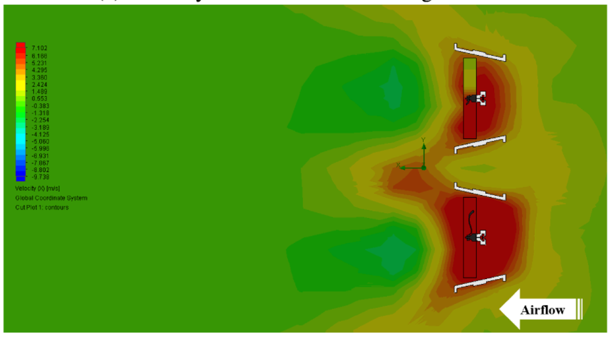


Fig. 3: Design variables of the duct fan covers to increase propulsion efficiency and thrust power: The d_d is a depth of the duct fan, the d_b is a distance between the left and right duct fans, and the d_i and d_o are an outlet and inlet dimension of the duct fan.



(a) Velocity contours when moving forward



(b) Velocity contours when moving backward

Fig. 4: CFD analysis of the 3D-printed duct fans.

and its outlets point to the inlet of the filter. This creates circulation and increases the area of attraction, enabling to collect HABs without a physical contact and keep them in the mesh net physical filter system.

1) Duct Fan Design: As with Fig. 3, the duct cover consists of small 3D-printed parts that compresses air for the propulsion of the fans. The d_d is a depth of the duct fan, set as $0.2\,\mathrm{m}$, and the d_b is a distance between the left and right duct fans, set as $0.55\,\mathrm{m}$. The values of d_d and d_b were determined with a consideration of the maximum width of the USV platform. The static thrust is about $10\,\mathrm{kgf}$, and speed is approximately $1000\,\mathrm{rad/s}$. The d_i and d_o are an outlet and inlet dimensions of the duct fan that were calculated by the successive linear programming (SLP) optimization [17] with the Momentum Theory to minimize the efficiency loss of the duct fan as follows [18]:

$$\text{Minimize:} \quad f(d_i, d_o) = 1 - \eta_p \tag{1}$$

$$\begin{aligned} \text{Subject to:} \quad & g_1(d_i, d_o) = d_{i_{min}} \le d_i \le d_{i_{max}} \\ & g_2(d_i, d_o) = d_{o_{min}} \le d_o \le d_{o_{max}} \\ & g_3(d_i, d_o) = r_{min} \le \tfrac{d_i}{d_o} \le r_{max} \end{aligned}$$

where g_1 is that d_i should be less than $d_{i_{max}}$ and greater than $d_{i_{min}}$, g_2 is that d_o is less than $d_{o_{max}}$ and greater than $d_{i_{min}}$, and g_3 is that the ratio of d_i and d_o is between r_{min} and r_{max}. For these constraints, we limited that $d_{i_{max}}$ is $0.381\,\mathrm{m}$ ($\approx 15\,''$), and $d_{i_{min}}$ is $0.3048\,\mathrm{m}$ ($\approx 12\,''$) that are maximum and minimum inlet diameter of the duct fan, respectively. Also, $d_{o_{max}}$ is $0.381\,\mathrm{m}$ ($\approx 15\,''$) and $d_{o_{min}}$ is $0.254\,\mathrm{m}$ ($\approx 10\,''$) that are maximum and minimum outlet diameter of the outlet, respectively. Additionally, r_{min} and r_{max} are to set a minimum and maximum ratio of the outlet and inlet sizes, and they were set as 1 and 2, respectively. These variables and values were determined by a careful consideration of the limited hardware size and importance of moving forward and backward motions the. It is worth noting that in the ratio, we added more weight to the moving forward motion than the backward motion because the USV typically moves forward although it sometime needs to move backward while maneuvering and collecting algae.

In the optimization, η_p is a propulsion efficiency that can be expressed by:

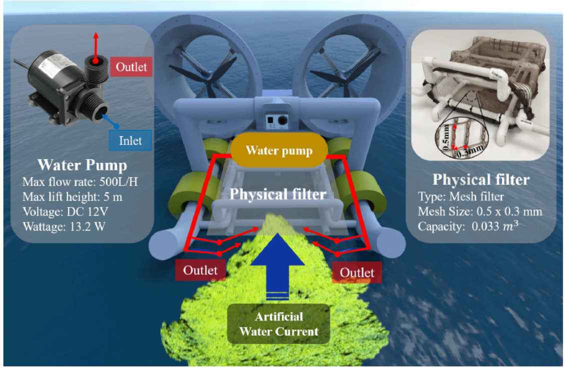
$$\eta_p = \frac{P_{flight}}{P_{fan}} = \frac{T \times \omega}{P_{loss} - P_{gain}} \tag{2}$$

$$P_{loss} = \frac{\nu_e^2 d_c^2 \frac{\pi}{4} \omega \rho}{2} \tag{3}$$

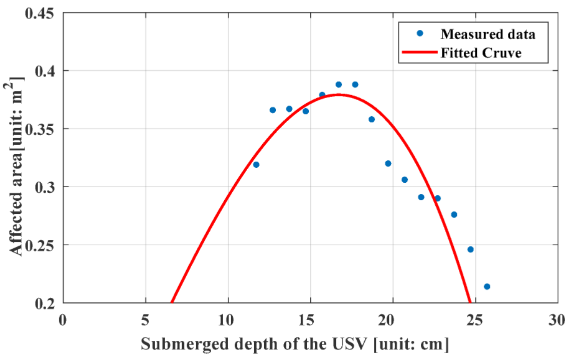
$$P_{gain} = \frac{M}{2} \times \omega^2 \tag{4}$$

where P_{flight} is the power required for operation, P_{loss} is the power lost by the propellers, P_{gain} is the power acquired by the propellers, d_c = $0.3048\,\mathrm{m}$ decided by the propeller size, v_i=$0.01\,\mathrm{m/s}$ is a desired velocity, Δv is a velocity difference ($\Delta v = v_e - v_i$), and ρ is an air density as $1.2\,\mathrm{kg/m^3}$, ω is an air speed, Q is an air volume, T is a thrust, and M is a mass flow. As a result of the optimization algorithm, the d_i and d_o are $0.33\,\mathrm{m}$ (=13 $''$) and $0.28\,\mathrm{m}$ (=11 $''$), respectively.

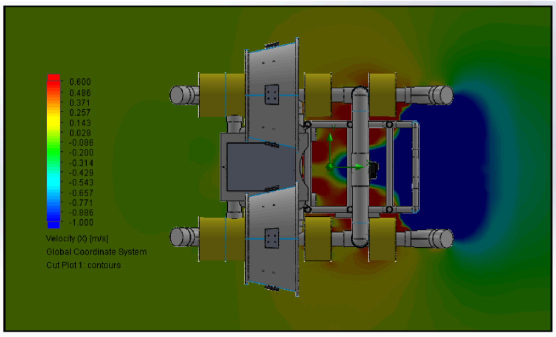
The calculated values were applied on the design of the duct fan, and then we analyzed it using the CFD simulation program to validate that the 3D printed duct fans have the ability to generate enough thrust speed/force and to compress air for forward and backward propulsion. Fig. 4a and Fig. 4b are results of the CFD analysis when moving forward and moving backward, respectively. In the moving forward analysis, the averaged thrust force was $10.444\,\mathrm{N}$, and the maximum speed was $11.166\,\mathrm{m/s}$. On the other hand, in the moving backward analysis, the averaged thrust force is



(a) Overall system diagram



(b) CFD analysis with varying submerged depth



(c) CFD simulation

Fig. 5: The proposed water suction mechanism: (a) the overall system diagram, (b) CFD analysis on the suction area by varying a submerged depth, and (c) CFD simulation with the optimal submerged depth, resulting that the suction area is $0.388\,\mathrm{m}^2$.

$4.184\,\mathrm{N}$ and maximum speed is $5.933\,\mathrm{m/s}$. These results were expected as we designed the duct fan to be more advantageous to the moving forward motion.

From this CFD analysis, we found that the 3D-printed duct fans can generate sufficient thrust speed and propulsion to enable the USV platform to move forward as well as backward. The design files for the duct fans can be downloaded at our online repository[1].

[1]3D-printed duct fan design files: https://github.com/SMARTlab-Purdue/Harmful-Algae-Removal-USV/tree/master/DuctFanDesign

2) Water Suction Mechanism: The water suction mechanism is one of the cores of the proposed USV in that it significantly improves the performance of removing the HABs. It is difficult for traditional surface vehicles to collect HABs near shore areas due to their hardware limitations, such as underwater thrusters and passive collection methods. On the other hand, the proposed USV with the water suction mechanism is able to actively collect the HABs from the areas without physical contact by means of generating artificial water current as illustrated in Fig. 5a. This artificial water current is generated with a submersible water pump installed at the USV. The maximum flow rate of the pump is $800\,\mathrm{L/h}$ (210 GPH), and the maximum lift height is $5\,\mathrm{m}$. The outlet of the pump is connected with rubber hoses and mounted with a 30-degree nozzle at the end of the hose, and then spread the water coming from the inlet toward the mesh-based physical filter system mounted at the center of the platform. Thus, the water suction mechanism makes easier to collect HABs to the filter system.

The performance of the proposed water suction mechanism is affected according to the submerged height of the USV. In order to compute the maximized area of the water suction, we carried out CFD simulation analysis. The suction area is defined as an area where the velocity of the medium is negative and where is enclosed with the body of the USV except the entrance of the filter. To solely validate water circulation system, the USV was set to be stationary. The volume flow rate of the water from 7 outlets was set as $800\,\mathrm{L/h}$ (210 GPH). The flow simulation considered both laminar and turbulent flow of water. The gravity was set as $-9.81\,\mathrm{m}^2/\mathrm{s}$.

The result of the CFD analysis is graphically summarized in Fig. 5b. The analysis reveals that the suction area increases as the USV submerges and reaches the maximum when the USV was submerged to the depth, a length between the water surface and the bottom of the USV, between 16cm to 17cm, and it gradually decreases as the submerged depth increases. Based on this CFD simulation analysis, we determined the appropriate amount of buoyancy (i.e., the number of floating buoys and adding weight) and the location of the water hoses.

Fig. 5c shows the result of CFD simulation with the designed water suction mechanism when the USV was submerged to the optimal depth, resulting that the suction area is computed as $0.388\,\mathrm{m}^2$.

B. Control System

The developed USV allows two ways to communicate with an operator: 1) radio frequency (RF) communication, and 2) the robot operating system (ROS). The RF communication has a priority over the ROS system for a safety issue. In the main control box (Fig. 1), a single-board computer (SBC) with an Atmega32 based Arduino board is housed to utilize the ROS system to communicate with the Arduino board and a ground station.

The Arduino board is in charge of concurrently controlling two fans, a water pump, and a radio receiver as shown in Fig. 6 (USV node). The speed of the duct fans is controlled with

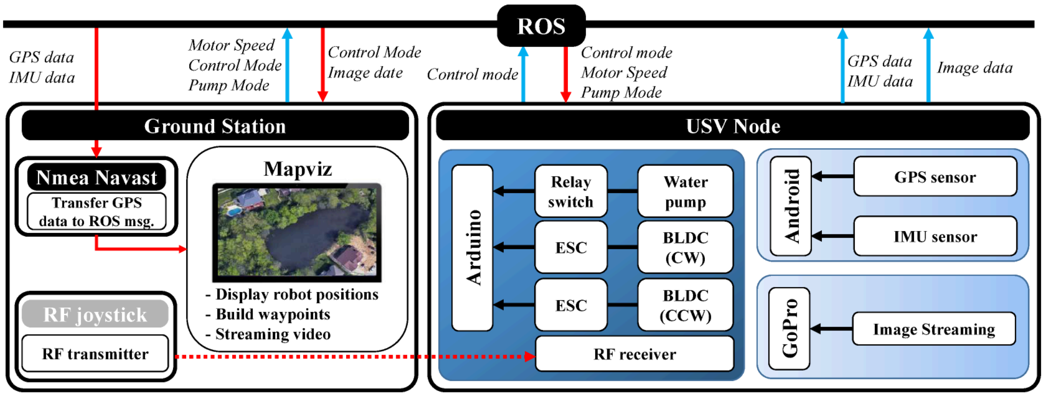
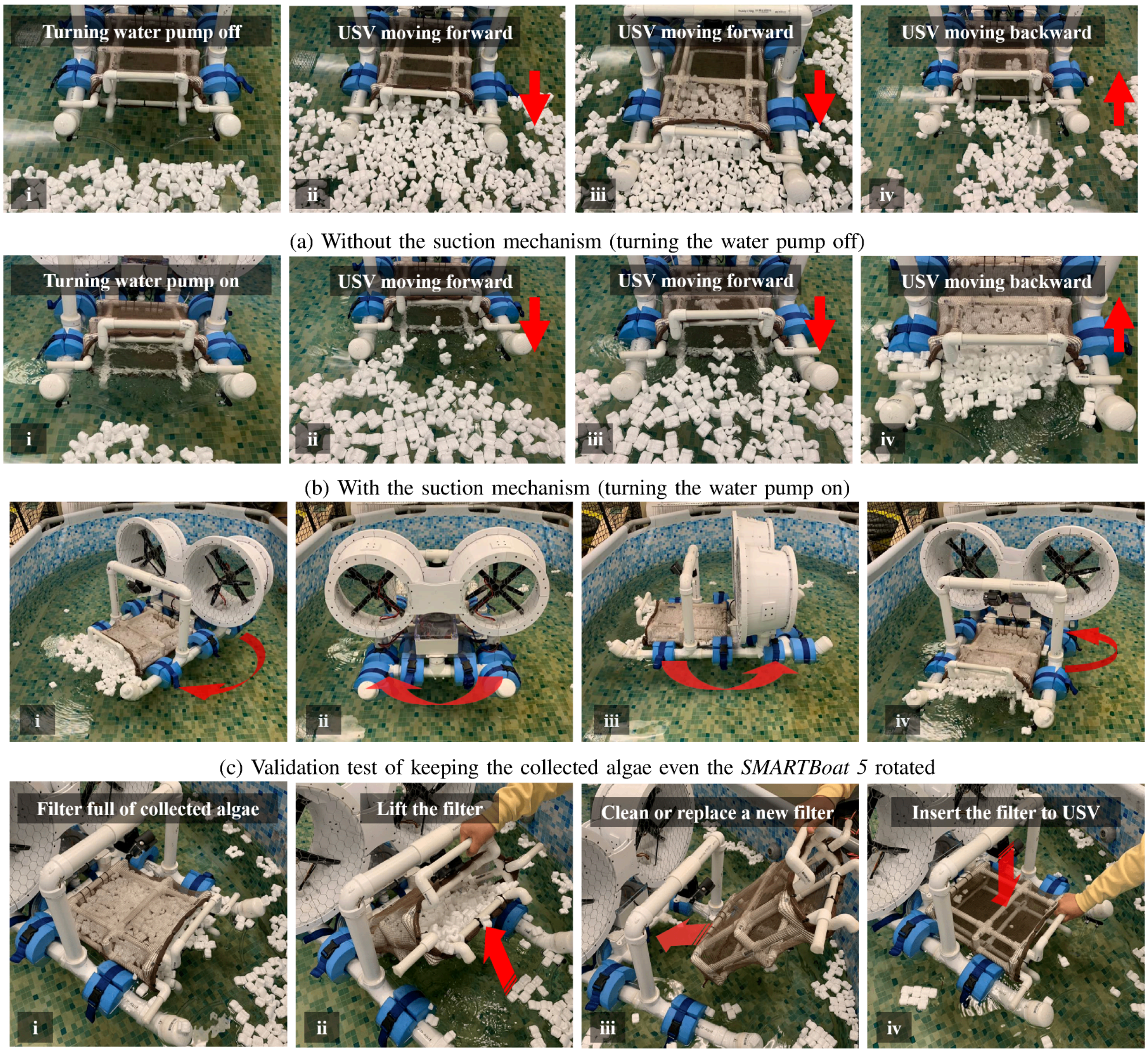


Fig. 6: Control system architecture of *SMARTBoat 5* using the ROS system.



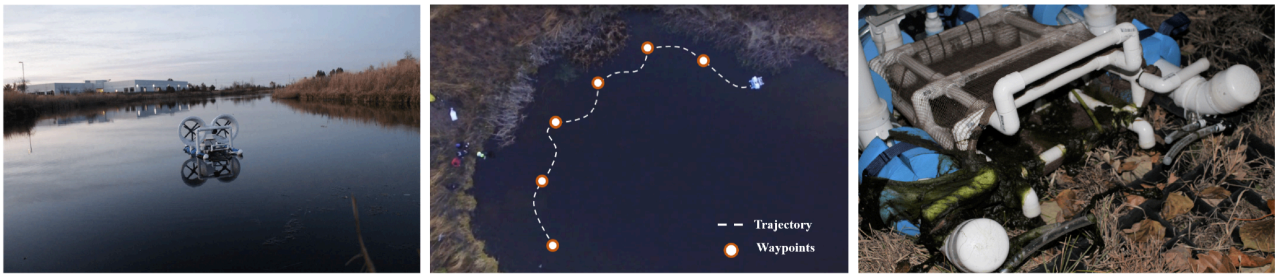
(a) Without the suction mechanism (turning the water pump off)

(b) With the suction mechanism (turning the water pump on)

(c) Validation test of keeping the collected algae even the *SMARTBoat 5* rotated

(d) Procedures to disassemble and assemble the physical filter system

Fig. 7: Experiments on the water suction mechanism and physical filter system, i.e., algae collector: (the figures are displayed in sequential order from left to right).



(a) Mobility test (b) Trajectory and waypoints during the test (c) Collected algae during the test

Fig. 8: Mobility and usability tests in a real-world application at the Purdue Research Park, West Lafayette, IN, USA. A full experiment video is available at http://smart-laboratory.org/docs/oceans19-habs.mp4.

electronic speed control (ESC). The water pump generating artificial water current is controlled by a relay switch via a GPIO pin of the Arduino board; it is turned on or off based on the binary command sent by the RF-based remote controller or the ROS standard messages from a ground station. The Arduino source codes used in the *SMARTBoat 5* can be downloaded at our online repository[2].

In terms of GPS and IMU data, the *SMARTBoat 5* utilizes an android device to get accurate and filtered data. The data is shared with the ROS system, and then displayed on Mapviz GUI, ROS-based visualization tool for visualization of GPS and IMU messages [19], allowing to track and display the current location and status of the USV.

III. Experiment and Results

A. Water Suction Mechanism Tests

In order to validate the performance of the proposed water suction mechanism, we carried out various lab experiments. The experiments were conducted with the indoor swimming pool where styrofoams were spread nearby its boundaries that play the role of algae. In the first experiment, we turned the water pump off and commanded the USV to approach the boundaries of the pool. As moving forward, the USV was able to collect some styroforms, but we observed that the amount was not great, and they were hard to collected. As moving backward, most of the collected styrofoams came out form the physical filter system, and the USV failed to keep them. This experiment is shown in Fig. 7a. In the second experiment, we turned the water pump on and commanded the USV to approach the boundaries of the pool. As a result, the USV was able to collect significant amount of styroforms as moving forward. Furthermore, the surrounding styroforms were collected even when the USV was stationary. As moving backward, almost of the collected styrofoams were kept in the physical filter system. This experiment is shown in Fig. 7b.

In the third experiment, we rotated the USV carrying the collected styroforms to evaluate the function of keeping the collected algae from coming out from the physical filter system. As a result, the USV was successfully able to keep the collected stroforms even while rotating. This result is shown in Fig. 7c. With these various lab experiments, we validated that the proposed water suction mechanism is effective.

[2]ROS based Arduino source code: https://github.com/SMARTlab-Purdue/Harmful-Algae-Removal-USV/tree/master/ArduinoSourceCode

B. Mobility and Usability Tests

Mobility and usability tests for the developed USV platform were performed at the Purdue Research Park, West Lafayette, IN USA, as shown in Fig. 8. We remotely commanded the USV to move along shorelines in order to validate its effectiveness in terms of the mobility and usability. One of the trajectories of the USV during the tests is depicted in Fig. 8b, where the USV moved a total of approximately $30\,\mathrm{m}$. We obtained this trajectory from the camera of the flying drone. As a result, the USV was successfully able to move along the shorelines even in shallow water while moving forward as well as backward. This validates that the thrust force produced by propellers was enough for the USV platform to maneuver in real applications and that the designed duct fans allow forward and backward movements although they are advantageous to the forward movement.

In addition, the USV was able to actively collect a good amount of algae with the proposed water suction system while moving (Fig. 8c). Furthermore, we observed that some distant algae were absorbed by the water suction mechanism without any physical contact. This validates that the water suction mechanism is also effective and that the proposed USV platform can safely and immediately control algae in real-world applications.

IV. Conclusion and Future Works

We introduced an eco-friendly USV with a water suction mechanism, called *SMARTBoat 5*, to control HABs in real-world applications. Lab and outdoor experiments concerning the hardware prototype and the control system design were successful; the prototype demonstrated stability and mobility with the dual three-blade thrusters. In tests of mobility and usability control, the *SMARTBoat 5* successfully collected HABs in the target area, including shore area, using the developed water suction mechanism.

Notably, as the collection mass increased, greater drag caused an inaccuracy in movement control. Also, the target area contained a huge amount of algae, and a single USV was not enough to remove all the algae from the lake. However, this storage limitation can be overcome using a multi-USV system. In the future, we will improve the control system to deal with increasing mass of the platform due to the collection. In addition, we will develop a multi-robot team to overcome the storage limitation and cover larger areas by deploying a number of USVs cooperatively performing algae control.

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