Field Report: Autonomous Lake Bed Depth Mapping by a Portable Semi-submersible USV at Mt. Zao Okama Crater Lake

Atsushi Watanabe[1], Miwa Kuri[2] and Keiji Nagatani[1]

***Abstract*— This work presents a design and a field test result of a small USV system that has portability and wind tolerance for a lake bed depth mapping of volcanic crater lakes. The depth map of the crater lakes indicates an amount of water, crater wall caving, and volcanic upthrust, which is used for volcanic disaster prevention. However, todayfs depth surveillance is achieved by using a manned canoe on a lake in high-altitude, strong-winded, and restricted areas. This research is aiming to realize the autonomous Unmanned Surface Vehicle (USV) for volcanic crater lake surveillance in reducing risks to surveyors. In this research, the authors have developed the lightweight semisubmersible USV system with a high draft that has portability and wind tolerance. The result of a field test at Mt. Zao Okama Crater Lake is shown. A depth map of the north half of the Okama Crater Lake was autonomously measured by using the USV system.**

I. INTRODUCTION

A volcanic disaster is a critical problem for volcanic countries. In Japan, volcanic warnings and forecasts are issued by the Volcanic Observations and Information Center in the Japan Meteorological Agency based on field research by volcanologists. One of the targets of the volcanic observation is a status of crater and caldera lakes. Once the volcano erupts, water in these lakes might cause a flash flood and hydrovolcanic explosion. Observing such crater and caldera lakes are required for updating a hazard map in peacetime and an evacuation planning in an emergency.

For example, in the Mt. Zao Okama Crater Lake in Japan, the depth map of the crater lakes indicates an amount of water, crater wall caving, and volcanic upthrusts. This is achieved by using a manned canoe with a depth-sounding apparatus. In the recent field research of Mt. Zao in 2015 [1], the depth of the lake was around 25 meters. The canoe for the observation is carried and paddled by a human in high altitude, strong wind, and restricted area. This surveillance has risks of the slip dropping, being upset into the lake, and hypothermia.

This research is aiming to realize the autonomous volcanic crater lake depth mapping by a portable Unmanned Surface Vehicle (USV) for reducing risks to human surveyors. This research and development are according to the request from the volcanologists. They need a depth map with 1 meter of the accuracy of the estimation of the rough pondage. In this research, the authors developed a lightweight USV system that is easy to carry in a backpack by the human. The USV system is semi-submersible with two fixed thrusters under the water; it has a high draft to have wind tolerance. The result of a field test at Mt. Zao Okama Crater Lake is shown. A depth map of the north half of Okama Crater Lake was autonomously measured by using the USV system. The USV could be navigated autonomously without upset under 5 to 20 m/s of winds.

Fig. 1. Conventional Mt. Zao Okama Crater Lake surveillance by using manned canoe. Diameter of the lake is about 300 m.

II. RELATED WORKS

The development and field test results of the multi-USV system for the volcanic lake are reported [2]. In this report, a surface temperature of the Taal Lake in the Philippines was mapped by using five USVs structured with a single propeller in the air as a thruster. However, for the Okama Crater Lake, several different difficulties of USV surveillance exist:

- strong alpine wind
- a countermeasure to the corrosive water
- inaccessibility (only by walking is one allowed around Okama Crater Lake, and horse riding is allowed around Taal Lake)

Semi-submersible vehicles are used to reduce wind resistance, wave-making resistance, and the effect of waves, [3] and it is also used for USV systems [4]. Depth control of the semi-submersible vehicle is required, especially for high-speed navigation [5], [6].

For the control of the USV with two fixed thrusters, linearized modeling of the USV and a multiple-input-multiple-output control approach is reported [7]. On the other hand,

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in this paper, angular and linear velocity are separately controlled as independent variables based on the hydrodynamics of this type of USV.

III. CONCEPT OF THE USV FOR THE OKAMA CRATER LAKE

Table. I shows data on the Okama crater lake. To survey the Mt. Zao Okama Crater Lake, the main environmental requirements for the USV system are the following:

1) Transportability in the mountain
2) Wind tolerance for the mountaintop windblast
3) Countermeasure against the corrosive and acidic water

Since the target environment is on the mountain and also in the nature reserve area, the place is not reachable by automobiles. Also, such a place is windy, and the water of the crater lake is acidic and corrosive.

According to these requirements, the main design concept of the developed USV for the Okama Crater Lake is **a small, portable, electric USV**, **a semi-submersible boat structure with autonomous navigation** and **cheap, disposable thrusters (motors)**.

A. Portable small electric USV

In the target environment, all equipment required for the surveillance must be carried by the human by trekking. Therefore, the USV must be able to be packed in a backpack.

The internal combustion engine is not acceptable due to its transportability and the high altitude; an electric motor is used for thrusters of the USV.

The smaller size of the USV is better to reduce human effort, and the longer time of operation is better. The authors aimed to reduce the size of the USV and achieve 1.5 hours of operation time.

B. Semi-submersible boat structures with autonomous navigation

Due to the wind at the lake, a semi-submersible design was used to reduce wind and wave-making resistance. Since the semi-submersible boat has a small freeboard and the lake is not transparent, teleoperations by visual contact or remote camera are not suitable; thus, autonomous navigation is required.

C. Cheap, disposable thrusters

Since the water of the lake is corrosive due to the volcanic sulfurous acid present in it, the metal elements of the thruster are easily damaged. Therefore, using low-cost motors as directly driven thrusters and changing them after every use is reasonable.

TABLE I
DATA OF THE MT. ZAO OKAMA CRATER LAKE

Location	38.1365° N, 140.449472° E
Surface elevation	1,550 m
Width	320 ∼ 340 m
Max. depth	27.6 m (1968)

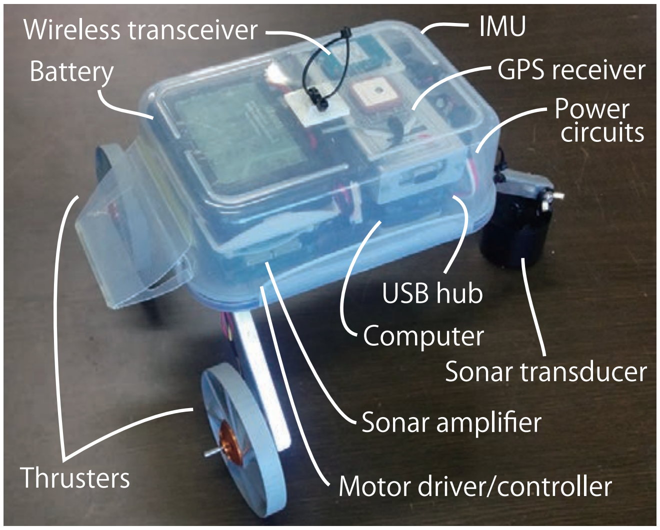

Fig. 2. The developed semi-submersible USV system and its components. Outer dimensions is 290 x 330 x 210 mm.

IV. DEVELOPMENT OF THE USV

A. Mechanism

Fig. 2 shows the picture of the developed USV system and its components. The developed USV system and its components. The outer dimensions of the USV are 290 x 330 x 210 mm, and it weighs 1.3 kg.

The system is semi-submersible. Since water blocks radio waves, antennae for communication and the GPS receiver must not be underwater. The draft of the USV is not actively controlled, and it is designed to be a few centimeters from the top surface at a translational velocity of 0.6 m/s.

The main body is a waterproof plastic box, and the bottom surface is an aluminum plate for the heat dissipation of internal electric circuits.

The USV has two fixed thrusters with mirrored propellers directly driven by brushless motors. These motors are sold as USV motor retails for a few dollars; the motor can be disposable even if it is damaged by corrosive water.

A teleoperation is available through specified low-power radio transceivers for an emergency situation.

B. Sensing and Control

The USV has a stick computer BOXSTCK1A32WFCR by Intel as a robot controller. The software system is structured on the ROS Kinetic framework on Ubuntu 16.04. The USV is autonomous and self-contained.

The equipped power source is a lithium iron phosphate (LiFePO4)-assembled battery (2.3 Ah, 13.2 V). It achieved roughly 1.5 hours of operation.

1) Feed-forward velocity control: The angular velocity of the USV can be measured at a high frequency by using IMU. However, the linear velocity is not directory observable. This system controls angular velocity with a closed-loop feedback from IMU and linear velocity with a hydrodynamics-based feed-forward.

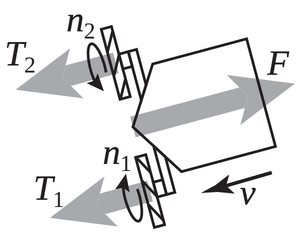

Fig. 3. Dynamics of the USV with two thruster rotational speed

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Force generated from thruster i is in a proportion of propeller rotational speed, and resistance of the water is in a proportion of the USV velocity.

$$\begin{aligned} T_i &\propto (n_i)^2 \\ F &\propto v^2 \end{aligned} \tag{1}$$

Water resistance force and thrust force are balanced where the translational velocity is constant ($\dot{v} = 0$).

$$\begin{aligned} F &= T_1 + T_2 \\ v^2 &= \begin{cases} k\left((n_1)^2 + (n_2)^2\right) & (n_1 > 0 \wedge n_2 > 0) \\ k\left((n_1)^2 - (n_2)^2\right) & (n_1 > 0 \wedge n_2 < 0) \\ k\left(-(n_1)^2 + (n_2)^2\right) & (n_1 < 0 \wedge n_2 > 0) \end{cases} \end{aligned} \tag{2}$$

Where the variable k is a composite of hydrodynamic parameters. This parameter can be obtained by a preliminary experiment with the following expression by measuring USV velocity on constant propellers' rotational velocity.

$$v^2\Big|_{n_1=n_2=n} = 2kn^2 \tag{3}$$

Thus, the translational velocity of the USV can constantly be controlled under the constraining of expression (2), which can be plotted as shown in Fig. 4, allowing angular motion.

Each thruster rotational velocity n_i is P-controlled by using desired translational velocity v and measured angular velocity ω of IMU by following expressions, which are a parametric representation of Fig. 4.

$$x = -k_p(\omega^{ref} - \omega) \tag{4}$$

$$n_1 = \begin{cases} \dfrac{-\left(v/\sqrt{k}\right)^2 - 2x^2}{2\sqrt{2}x} & (x < -\dfrac{v}{\sqrt{2k}}) \\ \dfrac{\left(v/\sqrt{k}\right)^2 - 2x^2}{2\sqrt{2}x} & (x > \dfrac{v}{\sqrt{2k}}) \\ \dfrac{-x + \sqrt{\left(v/\sqrt{k}\right)^2 - x^2}}{\sqrt{2}} & otherwise \end{cases}$$

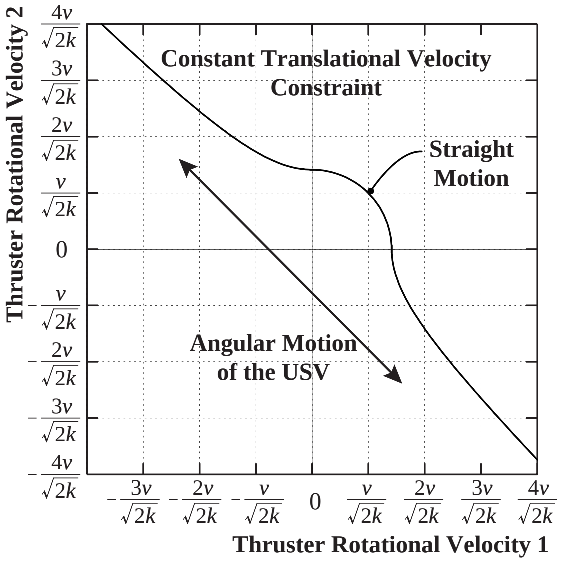

Fig. 4. Constant translational velocity constraint of two thruster rotational speed.

$$n_2 = \begin{cases} \dfrac{-\left(v/\sqrt{k}\right)^2 + 2x^2}{2\sqrt{2}x} & (x < -\dfrac{v}{\sqrt{2k}}) \\ \dfrac{\left(v/\sqrt{k}\right)^2 + 2x^2}{2\sqrt{2}x} & (x > \dfrac{v}{\sqrt{2k}}) \\ \dfrac{x + \sqrt{\left(v/\sqrt{k}\right)^2 - x^2}}{\sqrt{2}} & otherwise \end{cases} \tag{5}$$

Where k_p is the proportional gain of angular velocity feedback control.

Herewith, angular and linear velocity relative to the water flow are independently controlled by using the expression (5). The velocities of the thruster propellers are controlled by VVVF by using TF-2MD3-R6 from the T-frog project.

A quantitative evaluation of the feed-forward velocity control is not yet done. It remains as a future work.

2) Localization: The USV has a GPS receiver EVK-6T by u-blox and an IMU module RT-BT-9AXIS-00 by RT Corporation. The pose of the USV is composed of the IMU pose, and ENU coordinates the GPS position. IMU pose is calculated by using imu_filter_madgwick ROS node [8] from the gyro, accelerometer, and magnetometer sensor data.

3) Path tracking control: A path for the autonomous navigation can be given as a kml file. The authors used Google MyMaps as a kml editor.

The motion of the USV is controlled by the linear feedback of distance, angle, and angular velocity errors based on the path-tracking control method for wheeled mobile robots [9]. Distance, angle, and angular velocity errors are calculated with the above localization result and given path. Since USV has relatively slower responsivity than wheeled mobile robots, the linear prediction of the USV state is implemented to reduce oscillation.

Fig. 5. USV path design on Google MyMaps. Designed paths are exported as a kml file. Note: a rope is stretched on an east-west centerline of Okama for conventional manned field-research. USV path must be designed to avoid the rope.

4) Depth measurement: A sonar transducer and amplifier are picked out from an off-brand fish finder. The directivity angle of the transducer is 45 degrees.

A logarithmically amplified echo signal in the amplifier is captured as an audio signal and stored in the robot controller.

Due to the small body size of the USV, the distance between the thrusters and transducer is short. Therefore, an electric noise of the motor drive significantly affects the S/N ratio of the echo signal through the water, even if the circuits are shielded and the power line is filtered. The USV completely stops the PWM switching in the motor driver for 5 seconds for each 10 meters of navigation to improve the noise floor of the signal.

V. FIELD TEST ON OKAMA CRATER LAKE

The authors performed a field test to confirm the operation of the system and measure the depth of Okama Crater Lake. The chance for the field test is two days per year, and the test of the robot should never disturb the manned field research.

TABLE II

ENVIRONMENTAL STATUS OF THE FIELD-TEST AT THE MT. ZAO OKAMA CRATER LAKE

Date	June 2, 2016
Air temperature	6.5°C
Water temperature	7.0°C
Wind speed	5 ∼ 10 m/s
Wind blast	around 20 m/s
Volcanic Alert Levels*	1 (advance notice)

* Volcanic Alert Levels is announced from Japan Meteorological Agency for each 34 special active volcanoes in Japan. Defined levels are 1: restriction in the crater, 2: restriction around the crater, 3: restriction in the mountain, 4: evacuation preparation alert, and 5: evacuation instruction.

A. Environmental status

Table. II shows the environmental status of the Okama Crater Lake during the field test. The water in the Okama had a surface circulation.

Since the Okama Crater Lake is placed in the restricted Umano-se Caldera area, the author participated with an investigative field research team. The author carried the USV, backup batteries, an emergency teleoperation host computer, and trekking gear packed in a 30-liter backpack.

The field test was conducted in parallel with conventional manned field research.

B. Path setting

Fig. 5 shows two depth mapping paths for USV designed on Google MyMaps: the north route and the south route.

In this surveillance of the Okama Crater Lake, a rope was stretched on the east-west centerline for conventional manned field research. The USV path was designed to avoid the rope.

C. Field-test results (North route)

Fig. 6 shows the result of the autonomous navigation of the north route. The test took 35 minutes with the desired control velocity of 0.6 m/s. The USV drifted from its path, especially at the end of the test. This was because the velocity of the USV was relative to the water flow. The velocity of the vehicle must be increased to improve its tracking performance.

Fig.7 shows depth data extracted with sonar signals and mapped using GPS data. Each point in the figure corresponds to one to five sonar measurements.

Fig.8 shows a comparison of sonar signals when the vehicle was in motion or stopped. The floor noise was improved about 20 dB when the motor driver was stopped.

During the test, the maximum roll and pitch angle of the USV was 0.09 rad.

D. Field-test results (South route)

Since the USV was strongly pushed to the southwest side due to the surface circulation, especially at the beginning of the south route, the author increased the velocity of the USV to 0.8 m/s. As a result, the USV went underwater because of the water pressure.

VI. DISCUSSION

A. Evaluation of the depth data

The depth data was also collected using a manned canoe for the conventional manual field-research. Fig. 9 shows the paths of the two measurements. In the manned canoe result,

TABLE III

COMPARISON OF THE MEASURED DEPTH BY THE MANNED CANOE AND THE USV

	manned canoe	USV
Point A	10.38 m	10.86 m
Point B	18.07 m	18.14 m

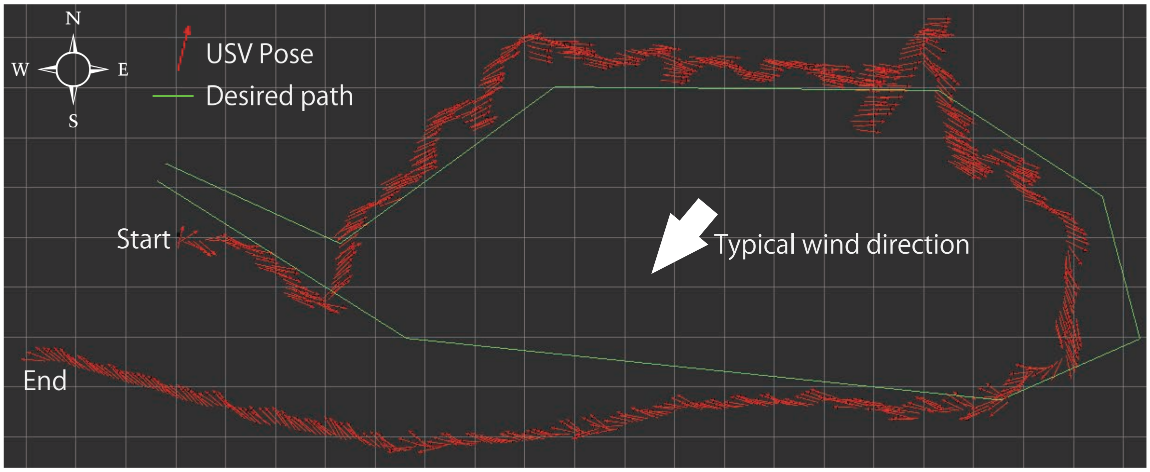

Fig. 6. The desired path and a resultant USV pose of the North route test.

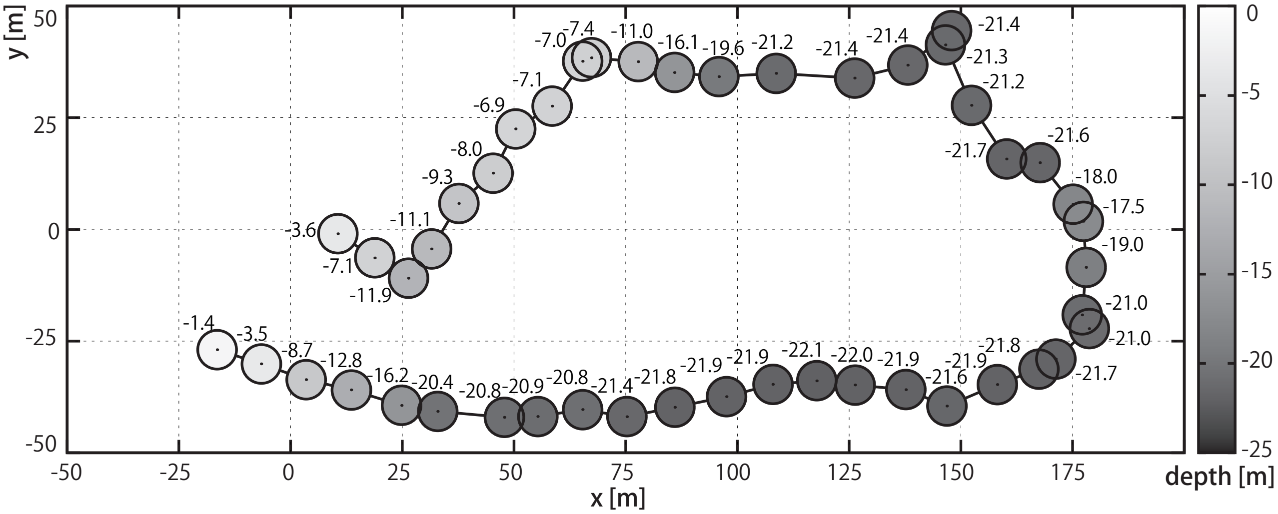

Fig. 7. Depth data extracted from sonar signal mapped by the GPS location.

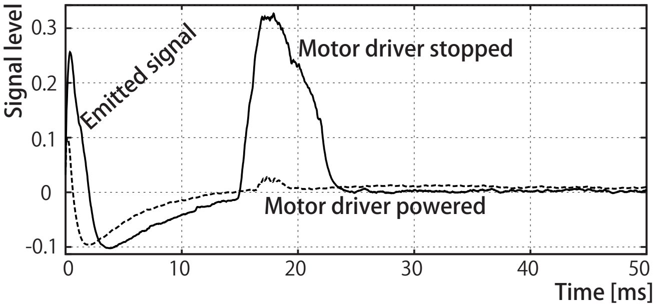

Fig. 8. Comparison of sonar signal between motor driver powered and stopped status.

there are several missing parts of the depth measurements. In these parts, the sonar transducer, which was floated and towed by the canoe, swung or upset.

Depth was measured by the canoe, and the USV at Points A and B, which are the crossing points of the paths, are shown in Table. III. The errors between these two measurements are 0.47 m and 0.07 m, which includes GPS positioning errors.

It is confirmed that the accuracy of the measured depth data is enough for the request from the volcanologists.

B. Lessons learned

Through the reported field test at the Okama crater lake, the effectiveness of the following features is confirmed. Also, several lessons are learned.

No upset occurs under 5 to 20 m/s of winds and blast during the tests, and the maximum angle of the swing was 0.09 rad. The effect of the wind can be reduced by the semi-submersible structure. However, the USV surfaces to the air or goes underwater at high speed without depth control.

The S/N ratio of the sonar signal can be significantly improved by stopping the PWM switching in the motor driver. Thus, it is confirmed that the motor can be placed close to the sonar transducer by stopping the PWM switching.

The sulfurous water of the Okama crater lake corrodes ferrous mechanical parts, as shown in Fig. 10. Since no

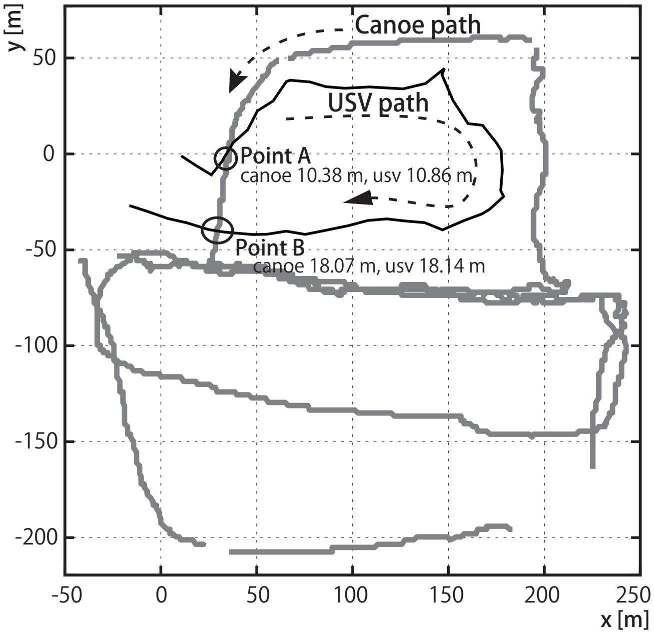

Fig. 9. Paths of the manned canoe and the USV. These paths have two crossing points

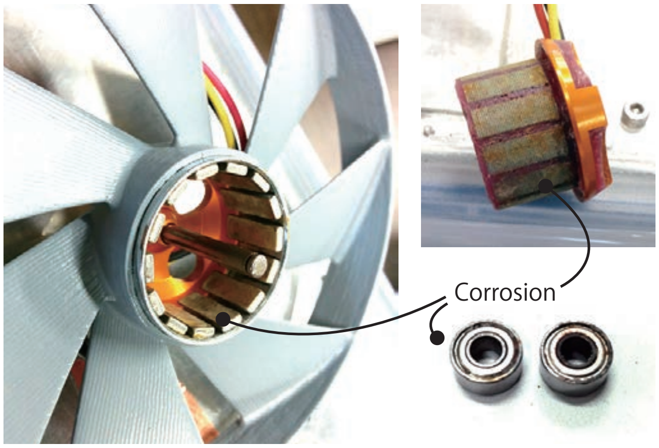

Fig. 10. Ferrous mechanical parts corroded by the sulfurous water of the Okama. The surface of the motor stator and the magnets and ball bearings are corroded.

other parts are affected, disposing of only motors looks a reasonable approach.

During the tests at the actual site, launching from near-shore makes the USV washed ashore. It must be dropped at offshore at beginning.

C. Future works

For the practical use of the developed USV system, the following issues remain for future works.

To increase path-tracking performance and survey a larger area of the lake, the USV's velocity must be increased. Depth control of the USV is required to achieve higher velocity. Also, a quantitative evaluation of the feed-forward velocity control method should be done.

The authors are planning to participate in the next field research on Mt. Zao in October 2016. In this term, depth mapping of the entire area of the Okama crater lake will be performed.

VII. CONCLUSION

This paper presented the design and the field test result of a small USV system that has portability and wind tolerance for the lake bed depth mapping of volcanic crater lakes. The developed autonomous USV for volcanic crater lake surveillance can reduce the risks to human surveyors.

The result of a field test at Mt. Zao Okama Crater Lake was shown in this paper. The depth map of the north half of the Okama Crater Lake was autonomously measured by using the USV system. It is confirmed that the developed USV system is able to create a depth map at the Okama Crater Lake. Also, it is confirmed that the developed USV system is easy to carry to the site and has wind tolerance.

ACKNOWLEDGMENT

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REFERENCES

[1] A. Goto, N. Tsuchiya, N. Hirano, T. Watanabe, T. Matsunaka, M. Kuri, M. Uno, A. Okamoto, K. Nakamura, and S. Machi, "Activization of zao volcano within the past 100 years and the present activity," in *Japan Geoscience Union Meeting 2016*, May 2016, pp. SVC47–P04. [Online]. Available: https://confit.atlas.jp/guide/event/jpgu2016/subject/SVC47-P04/programpage

[2] A. Valada, P. Velagapudi, B. Kannan, C. Tomaszewski, G. Kantor, and P. Scerri, *Development of a Low Cost Multi-Robot Autonomous Marine Surface Platform*. Springer, 2014, pp. 643–658. [Online]. Available: http://dx.doi.org/10.1007/978-3-642-40686-7_43

[3] K.-h. Mori, T. Hotta, K. Ebira, and X. Qi, "9. a study on semi-submersible high speed ship with wings : Its resistance characteristics and possibility," *Naval architecture and ocean engineering*, vol. 27, pp. 93–102, 1989. [Online]. Available: http://ci.nii.ac.jp/naid/110003861693/

[4] V. Bertram, "Unmanned surface vehicles - a survey," *Skibsteknisk Selskab, Copenhagen, Denmark*, pp. 1–14, 2008.

[5] H. Zhou, Y. Li, Z. Hu, and W. Li, "Identification state feedback control for the depth control of the studied underwater semi-submersible vehicle," in *IEEE CYBER 2015*, June 2015, pp. 875–880.

[6] P. Alleman, A. Kleiner, C. Steed, and D. Hook, "Development of a new unmanned semi-submersible (uss) vehicle," in *MTS/IEEE OCEANS 2009*, Oct 2009, pp. 1–6.

[7] J.-H. Park, H.-W. Shim, B.-H. Jun, S.-M. Kim, P.-M. Lee, and Y.-K. Lim, "A model estimation and multi-variable control of an unmanned surface vehicle with two fixed thrusters," in *MTS/IEEE OCEANS 2010*, May 2010, pp. 1–5.

[8] S. O. H. Madgwick, A. J. L. Harrison, and R. Vaidyanathan, "Estimation of imu and marg orientation using a gradient descent algorithm," in *IEEE International Conference on Rehabilitation Robotics 2011*, June 2011, pp. 1–7.

[9] S. Iida and S. Yuta, "Vehicle command system and trajectory control for autonomous mobile robots," in *IEEE/RSJ IROS '91. Intelligence for Mechanical Systems*, 1991, pp. 212–217 vol.1.