Development of an Unmanned Surface Vehicle for Remote Sediment Sampling with a *Van Veen* Grab Sampler

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***Abstract*—Sediment sampling is one of the essential activities to sediment monitoring, and it is typically performed manually. However, manual sediment sampling has limitations such as inaccessibility, contamination, or unavailability of the equipment. Based on these limitations, there is a need to make such manual sampling remotely through use of unmanned surface vehicles (USVs) that have been pertinent for various applications such as hydrographic survey and water quality monitoring with the growing advances in their technologies. In this paper, we propose a novel USV, the *SMARTBoat 7*, equipped with a *Van Veen* grab sampler for sampling sediment in water environments such as rivers, streams, lakes, and pond. We present details of the developed USV, including its physical specification and a control system architecture for remote sediment sampling. We validate the effectiveness of the developed USV through field experiments.**

***Keywords*—Unmanned surface vehicles, Sediment sampling, Grab sampler, *Van Veen* grab sampler**

I. Introduction

Sediment can contain significant information that can predict changes in water quality and be used for ecological and geochemical analysis [1]. For example, pollutant loadings from mining activities, such as heavy metals and PCBs (polychlorinated biphenyls), can persist for decades in riverine sediments [2]. We can measure pollutant concentrations from the sediments and prevent environmental pollution or develop environmental management solutions. Generally, sediment samples are collected from the bottom boundary layer (bed sediment) through manual sampling methods. However such methods often disturb the sediment being sampled and involve significant human labor and potential safety risks such as sampling from the contaminated area or flooding area. Also, inconsistent topography and bathymetry can cause inaccurate sampling.

With the recent advancements in the autonomy of the marine platforms, unmanned surface vehicles (USVs) have become an important part of several maritime applications. For example, in the last decade, USVs have been used for the cleaning of lakes [3], monitoring water stations located in oceans [4] and water quality monitoring for small and large aquatic areas [5] [6] [7] [8]. The work in [7] has developed a small size USV for in-situ measurements of deep water. An unmanned surface craft has been implemented in [8] for water sampling of coastal and estuarine systems and has been tested in southeastern Rhode Island Sound. A small USV can be transported for a long distance by an unmanned aerial vehicle (UAV), and such multi-robot coordination has been studied in [9].

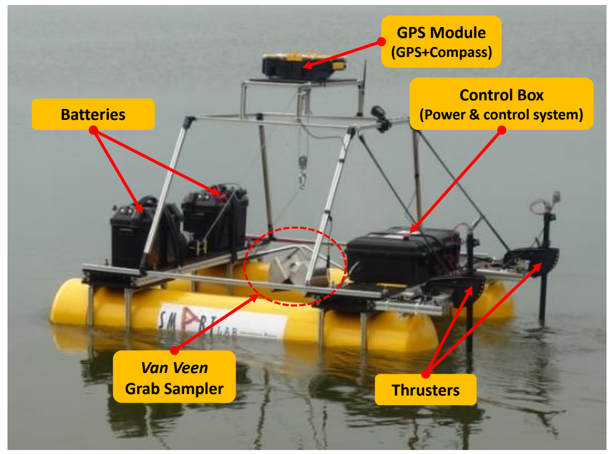


Fig. 1. The *SMARTBoat 7* integrated with a a *Van Veen* grab sampler for remote sediment sampling.

Compared to applications in the cleaning and water sampling tasks, a minimal number of applications can be found for sediment sampling based on USVs or autonomous underwater vehicles (AUVs). For example, remotely operated underwater Vehicles (ROVs) with the sediment sampling equipment has been proposed [10], [11], [12]. However, the results of the proposed approaches revealed the limitations on the sample collection, and the most platforms were primarily intended for use in oceanic environments [13], [14], [15], [16], [17] rather than smaller water bodies such as rivers, streams, lakes, ponds, and reservoirs. In short, they are too large and heavy to be practical in such environments. A sediment sampling aerial-ground robot team has been proposed in [18]; however, the robot team can only be applied around the shoreline.

In this study, we introduce a new USV platform for a remote sediment sampling in various water environments. The USV utilizes a *Van Veen* grab sampler [19] to collect sediment even in deep water effectively. A picture of the developed USV sampling the lake bed is shown in Fig. 1.

The contributions of the paper are outlined below:

- We propose a new USV platform capable of remote sediment sampling in various environments.

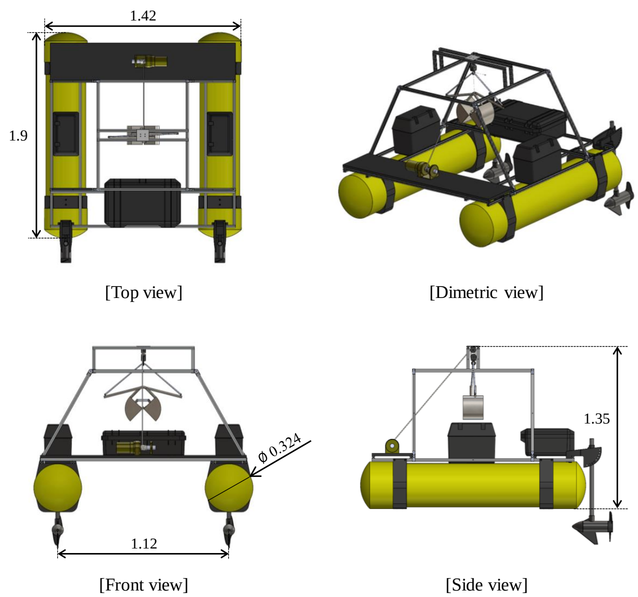


Fig. 2. Drawing of the proposed USV

TABLE I
HARDWARE SPECIFICATION OF THE *SMARTBoat 7*

Parameter	Value (m)
Length (overall)	1.9
Width (overall)	1.42
Height (overall)	1.35
Diameter of hulls	0.324
Draft	0.19
Distance between propellers	1.12

- We carry out field experiments and demonstrate the performance of the proposed sediment sampling system in terms of its maneuverability and usability.

II. USV FOR REMOTE SEDIMENT SAMPLING

We introduce a new USV platform, called *SMARTBoat 7*, for remote sediment sampling with a *Van Veen* grab sampler as shown in Fig. 1. The USV consists of a power and control system, a propulsion system, an anchoring system, the Global Positioning System (GPS) module, and the *Van Veen* grab sampler which is physically connected with the USV via a winch and a dolly. The base station communicates with the USV to remotely control and monitor the USV and the grab sampler.

A. Overview of the SMARTBoat 7

In this work, we present a systematic solution to sediment sampling of inland water bodies, in which the USV that actuated by two propellers is integrated with a sampling device that features a grab sampling method and adapts to a diversity of sediments. We adopt a cataraman structure based on twin hulls which can reduce roll and pitch motions to maintain the stability of the USV. The physical specification of the *SMARTBoat 7* is summarized in Fig. 2 and Table I. The overall length of the USV is 1.9m, and width is 1.42m. The power and control system in the Pelican case consists of batteries, single-board computer, motor controllers, and wireless antenna module. This system provides power to propellers, single-board computer, and motor controller and controls the propulsion system, anchoring system, and grab sampler. We separated the power system of winches for winches and the grab sampler and located on the front deck of the USV. This USV also carries the GPS module and the wireless antenna on the top part of the platform. The GPS module consists of the GPS and compass to navigate the USV. The wireless antenna is to communicate between the USV and base station (user) and monitor the sampling task.

B. Propulsion System

The propulsion system consists of two propellers by a set of 12V freshwater trolling motors. Thus, the *SMARTBoat 7* has a differential steering mechanism based on two inputs to control the velocity and heading.

Ideally, the differential thrust is zero when the USV maneuvers straight by operating two propellers at the same speed. To change the heading of the USV, two propellers (port and starboard side) need to generate momentum by the differential thrusts. However, the velocity also changes while changing the heading of the USV. Thus, coupling moment between the velocity and yaw rate of the USV occurs.

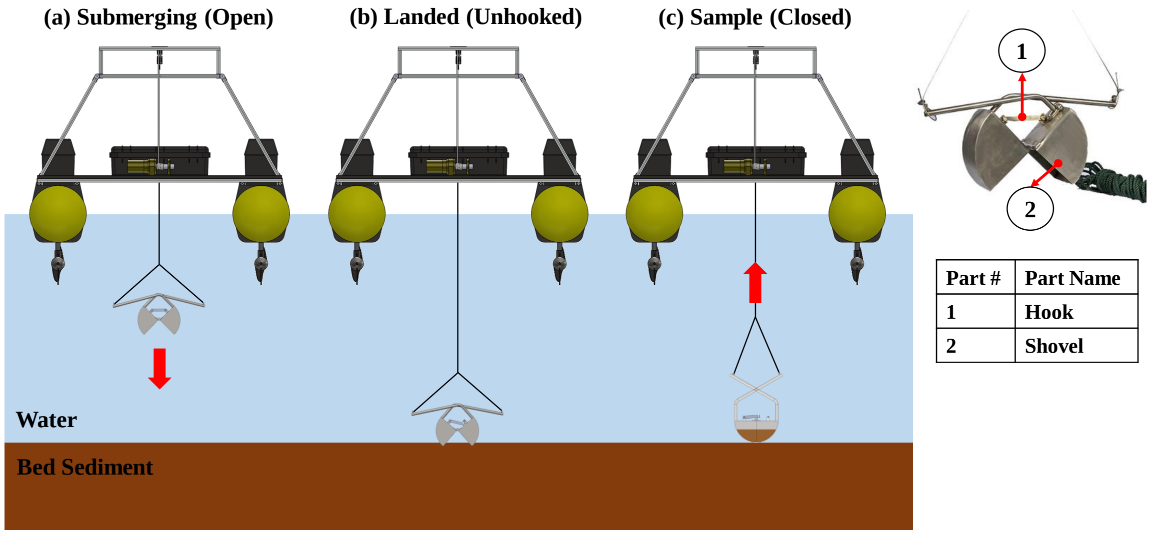
C. Specification of the Grab sampler and Anchoring system

A variety of grab samplers have been used to sample bed sediments such as *Shipek*, *Van Veen*, and *Peterson* sediment sampler. [19]. Grab samplers have advantages for collecting surface sediment and can cover a relatively larger area and more amount of sediment compare to other samplers. Also, it is appropriate for benthic, sediment oxygen demand, recent ambient conditions, and contamination investigation. In this study, we adopt a *Van Veen* grab sampler and integrate it to the USV platform as shown in Fig. 3. The hook holds the grab sampler to an open position. Once the hook touches the sediment at the bottom of the water, it unlocks itself. As the grab sampler gets pulled from the USV, it goes back to a closed position while sampling the sediment. The overall height of the sampler is 0.4m (closed), and the radius of the shovel part is 0.125m with a width of 0.15m. Thus, the maximum sampling volume of the *Van Veen* grab sampler is 1,630cm^3.

Staying inside of the boundary of the desired sampling area is necessary to establish an effective sediment sampling system. We adopt the anchoring system to maintain the position of the USV during the sampling process. Otherwise, the USV would wander by the wind or wave and likely move outside of the sampling area.

D. Control System Architecture

The *SMARTBoat 7* control system is sketched in Fig. 4. In the system, we use a laptop as the based station to monitor the real-time situation of the USV from the shore. A single-board computer is used as USV on-site controller in charge



Part #	Part Name
1	Hook
2	Shovel

Fig. 3. A procedure of the remote sediment sampling with a *Van Veen* grab sampler: (a) Submerge the sampler to the bottom of the water with an open position (the latch is hooked); (b) Once the sampler touches the bottom, the latch will be unhooked; and (c) When the latch is unhooked, the sampler will be closed automatically once the USV starts to retrieve the sampler and captures the sediment sample.

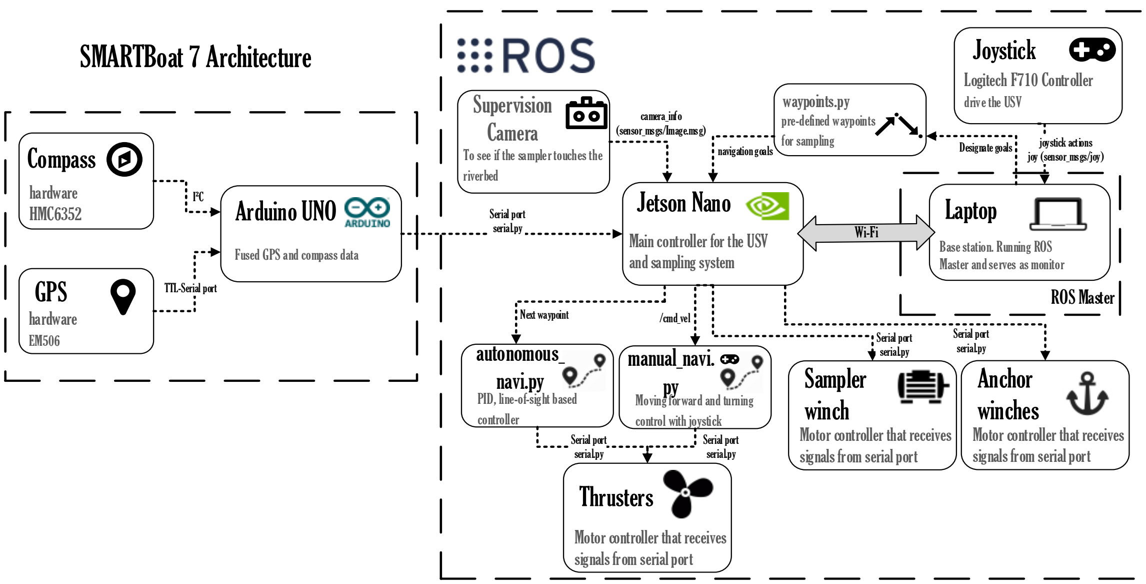


Fig. 4. Control system architecture of the proposed *SMARTBoat 7* for remote sediment sampling. The control system is operated with ROS allowing a remote control and an autonomous navigation of the *SMARTBoat 7*.

of sensors and several motors. To guarantee a secured long distance communication, we make the laptop as a *ROS Master* and connect the single board computer with it using Wi-Fi, which is proven to have a much longer communication distance than Zig-Bee and Bluetooth. As shown in Fig. 4, the sensor readings from the electronic compass and GPS sensor are fused by Arduino UNO and transmitted to the core controller, which is NVIDIA Jetson Nano. Other than Arduino UNO, the entire USV control system is built with the Robot Operating System (ROS), where two control modes for USV are realized, namely manual navigation mode and autonomous navigation mode. In manual navigation mode, we use a Logitech F710 joystick to control the robot, the commands are sent from the laptop to the remote single-board computer, and then used to drive the propellers. In terms of the autonomous navigation, we realized GPS-based navigation that enables the USV traversing in the workspace and visit each waypoint autonomously. The details will be elaborated in Sec. III.

To enable full functionalities of the USV in sediment sampling, we incorporated a DC motor for the *Van Veen* grab sampler, a DC motor for the anchor, and two DC motors

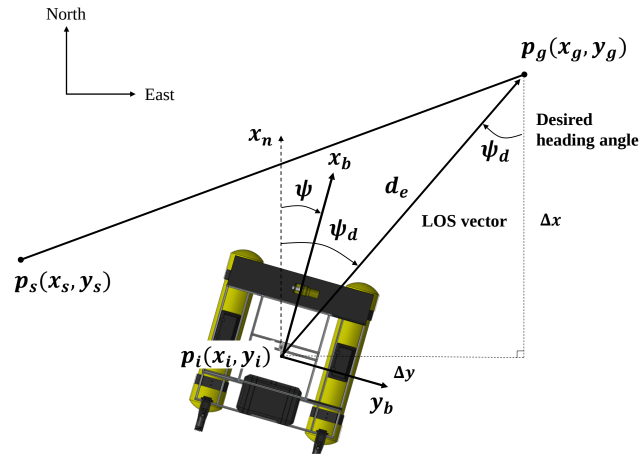


Fig. 5. LOS guidance where the desired moving angle ψ_d (angle between x_n and the LOS vector) is chosen to point toward the desired point $\mathbf{p}_g(x_g, y_g)$ from the start point $\mathbf{p}_s(x_s, y_s)$. We assume point $\mathbf{p}_i(x_i, y_i)$ as a current position of the USV and $\mathbf{p}_g(x_g, y_g)$ as the desired point.

as thrusters. Sampler winch and anchor winch modules are encapsulated as a *ROS node* for each of them, and they have to subscribe to the *joystick node* via the single-board computer. The *thrusters node* has to subscribe either *autonomous navigation node* or *manual navigation node*, depending on which is running at the moment. In order to accomplish multi-point sampling with the USV, we can designate several sampling points and encode them into a python file *waypoints.py*. This file can be accessed by the single-board computer and used by *autonomous navigation node*.

To secure a real time monitoring over the operation and in case of emergencies, we employ a laptop as the base station and to provide a real-time visualization. The laptop serves as the *ROS master* and can subscribe to the *supervision camera node* and monitor sampling process. Meanwhile, the configuration of waypoints can be determined or updated from the laptop, which is then shared by the single board computer for visiting.

E. Autonomous Navigation

To realize remote sediment sampling tasks and to generate smooth trajectory when a USV moves from one sampling point to the next, we adopt path following algorithm and design a control scheme (a proportional-derivative (PD) controller) that enables autonomous navigation. We devise the control law using the line-of-sight (LOS) guidance method with the heading error angle. The LOS vector from the vehicle to the next waypoint or any point between waypoints can be used to control the heading and path of the vehicle as shown in Fig. 5.

In the case of the *SMARTBoat 7*, the GPS gives the current position $\mathbf{p}_i = (x_i, y_i)$ of the USV and the compass measures the actual heading angle ψ of the USV. To calculate the desired moving angle ψ_d, we adopt Haversine formula [20], [21] that can calculate the desired heading angle ψ_d and distance error d_e from the latitude and longitude of the current position and goal position, as shown below:

$$\psi_d = \text{atan2}(\sin \Delta y \cos x_g \cos x_i \sin x_g - \sin x_i \cos x_g \cos \Delta y), \tag{1}$$

$$d_e = 2R \cdot \text{atan2}(\sqrt{a}, \sqrt{1-a}), \tag{2}$$

where $\mathbf{p}_i = (x_i, y_i)$ is the current location, and $\mathbf{p}_g = (x_g, y_g)$ is the goal position. Δx and Δy are the difference in latitude and longitude, respectively. The Haversine $a = \sin^2(\Delta x/2) + \cos x_i \cdot \cos x_g \cdot \sin^2(\Delta y/2)$, and R is the radius of the earth and $R = 6,371$ km. Then, we can define the heading error as,

$$\psi_e = \psi - \psi_d. \tag{3}$$

To maintain the desired heading angle, if the heading error is greater than 0, i.e., $\psi_e > 0$, we increase the speed of the port side thruster, and vise-versa based on the PD controller.

The heading error ψ_e is the difference between the heading angle (ψ) and desired angle (ψ_d), and the PD controller is formulated as below and used to align the forward direction of the USV with the desired angle ψ_d:

$$\dot{\psi} = -K_p^{\psi} \cdot \psi_e - K_d^{\psi} \cdot \dot{\psi}_e, \tag{4}$$

where $\dot{\psi}$ is the angular velocity, K_p^{ψ} and K_d^{ψ} are proportional and derivative gains for the steering angle errors, respectively.

In terms of the linear velocity ν, we use the proportional control method as below:

$$\nu = \begin{cases} K_p^d \cdot d_e, & \text{if } d_e \geq d_0, \\ 0, & \text{if } d_e < d_0, \end{cases} \tag{5}$$

where K_p^d is the proportional gain for the controller, and d_0 is a preset threshold to stop the USV from moving away from the goal.

III. Field Experiment and Results

In this section, we present a field experiment process and results to evaluate the effectiveness of the developed USV and its sampling capabilities in an open water body. This field experiment was carried out at Lake Harner ($44°95'58.8''N$, $86°95'53.5''W$) located in the vicinity of Purdue University Main Campus. The test site was selected based on various factors such as accessibility, depth, and the availability of sediment.

We carried out the following two tests with different purposes: 1) remote control test to validate manoeuvrability and sampling capability of the developed USV, and 2) navigation test to validate autonomous navigation capability of the developed USV.

A. Remote Control Test for Maneuverability and Sediment Sampling

The primary purpose of the remote control test was to evaluate manoeuvrability and sediment sampling capability of the *SMARTBoat 7*. For this test, we set the start point at the base station: $\mathbf{p}_s = (40°26'51.7''N,\ 86°52'02.0''W)$. Next, we selected four waypoints:

- $\mathbf{p}_{g1} = (40°26'53.6''N,\ 86°52'02.3''W)$
- $\mathbf{p}_{g2} = (40°26'53.6''N,\ 86°52'02.3''W)$
- $\mathbf{p}_{g3} = (40°26'53.6''N,\ 86°52'04.3''W)$
- $\mathbf{p}_{g4} = (40°26'52.6''N,\ 86°52'03.7''W)$

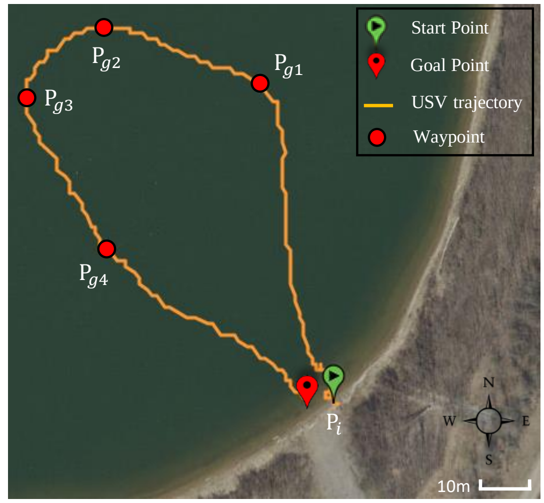
as candidate sampling locations, as shown in Fig. 6(a). We operated the joystick to navigate the USV to visit these waypoints. Even though the *Van Veen* sampler is an ideal tool for the sediment sampler, as it protects the sample in the best way from being polluted and works without actuator, it can be used only for a *one-shot* sampling. Therefore, we selected $\mathbf{p}_{g4}$ that is the last waypoint as the sampling point. The sampled sediment is shown in Fig. 7. The USV's travelling trajectory was smooth as we operated via the joystick, and the real location is transmitted back to the base station.

The remote control was supported by ROS worked over the Wi-Fi in order to achieve a longer communication range. After the USV was driven to the point to be sampled, the operator manually lowered the *Van Veen* grab sampler until it reached the lake bed. In order to identify whether the sampler has reached the lake bed or not, the visual feedback from the on-board camera was used, and the operator received the feedback via a Laptop. Based on the visuals of the tension in the wire holding the sampler, it was possible to find whether the sampler reached at the lake bed or not.

The key metric to determine the performance of the sampling task is the weight of the captured sample. We captured a sufficient amount of sample, weighing 850g. This quantity is more than the expected amount of 500g of sample required for the purpose of pollution monitoring by the agricultural scientist [22]. Also, based on the visual feedback by the camera monitoring of the sampler, it was able to observe that the collected sample remains intact and no dropping of the sample took place despite of the motion of the USV. Deploying the sampler from the USV and the sample collected from the experiment are shown in Fig. 7. The farthest point that the USV reached, in our test, was 84m. The entire trip took 16 mins, including 7 mins spent on the in place sampling at $\mathbf{p}_{g4}$. This sampling point was approximately 45m distance from the shore and based on the operation and feeding rate of the winch (3m/min), we can assume that the depth of the sampling point was approximately, 9m. To tackle the issue of *Van Veen* sampler and enable continuous sampling, we are currently developing a more advanced motor-driven sampler that can perform multiple samplings in one travel.

B. Autonomous Navigation Test

After the success of remote control test, we carried out the autonomous navigation test for the *SMARTBoat 7*. We kept the start point same as the remote control test at $\mathbf{p}_s = (40°26'51.7''N, 86°52'02.0''W)$ and the goal point as $\mathbf{p}_g = (40°26'53.5''N, 86°52'01.4''W)$, which is 57.4m in distance. We set the threshold d_0 for (5) as 4m in the test, considering the errors in GPS localization. We had originally planned to sample sediment at the goal position; however, due



(a) USV maneuvering and remote control test

(b) Autonomous navigation test

Fig. 6. Trajectories of the USV during the experiments in Lake Harner: (a) USV was navigated with four waypoints using the remote control mode. In this experiment, we tested its maneuverability and performed a sediment sampling at $\mathbf{p}_{g4}$; and (b) Trajectory of the USV during the autonomous navigation test.

to the technical issue, we could not operate the grab sampler during this autonomous navigation test. Nevertheless, we could validate that the USV was able to travel to the goal destination and hover there. The trajectory of the USV was depicted in Fig. 6(b). The USV deployment time consumed 2 mins.

A full experiment video is available at http://smart-laboratory.org/docs/oceans19-sampling.mp4.

IV. Conclusion and Future Work

In this paper, we introduced the new USV, called the *SMARTBoat 7*, for remote sediment sampling with a *Van Veen* grab sampler. We presented details of the developed USV, including its physical specification and a control system architecture. The designed control system architecture is based on ROS, and the autonomous navigation system is based on the

(a) *Van Veen* grab sampler from the USV

(b) Collected sediment sample

Fig. 7. Sediment sampling results: (a) Deployment of *Van Veen* grab sampler; and (b) Sediment sample collected with a *Van Veen* grab sampler, weighing 850g.

LOS guidance method and PD controller. The field experiment was carried out with the two test scenarios: 1) remote control test, 2) autonomous navigation test to demonstrate the proposed sediment sampling system and autonomous capability. As a result, we validated the performance of the proposed system in terms of its maneuverability and usability. We expect that this newly introduced remote sediment sampling system will be widely used for safe and effective sediment sampling for multiple applications including environmental monitoring and historical analysis.

As future work, we will attempt to improve the *SMARTBoat 7* so that it can achieve a fully autonomous sediment sampling. One example includes adding a tension sensor to the wire holding the sampler and making the sampler winch operation autonomous. We will deploy double anchors to the *SMARTBoat 7* to secure further maintaining the position of the USV while sampling even in the environment which has wind and current. In order to improve the current controller for the stability and robustness of the USV, we will also carry out the modeling based system identification and motion control.

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