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RESEARCH ARTICLE

Drone-Based Automatic Water Sampling System

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ABSTRACT Water sampling is a fundamental practice for obtaining essential environmental data, enabling the analysis and quality testing of water from natural or industrial sources. It is vital in understanding water quality changes over time, identifying contaminant sources, and supporting water management plans. Traditional sampling methods, including spot (bottle) sampling and in-situ readings, can be labor-intensive and limited by accessibility. To address these challenges, the utilization of drones has emerged as an innovative approach. Drones offer the potential to automate field quality control and streamline water sampling efforts for data collection in diverse water environments. This paper focuses on the design and development of a water sampling system integrated with a drone, featuring an automatic lock mechanism activated after rigorous field quality control, ensuring the reliable collection of water samples in various scenarios.

INDEX TERMS Water sampling, field quality control, sampling device.

I. INTRODUCTION

Water sampling for laboratory examination is essential in various circumstances, providing a crucial starting point to obtain relevant environmental data [2], [3]. It involves collecting a water sample from natural or industrial sources for analysis and quality testing. The data derived from water sampling plays a crucial role in providing valuable insight. This enables observation and measurement of changes in water quality over time, and identifying acidity and alkalinity levels. Additionally, water sampling aids in the identification of contaminated sources and supports the development and refinement of efficient water management [4], [5].

Conducting traditional water sampling and performing in situ physicochemical readings requires considerable manual labor, making them labor-intensive. The limited accessibility to the sampling areas hinders the execution of these methods [6], [7]. Moreover, difficulties arise especially in harsh and risky environment such as volcano crater lake monitoring. Data from volcano monitoring provide essential information that helps researchers in forecasting possible disasters [8], [9], [10]. In this case, utilizing unmanned aerial systems reveals commendable results for close proximity monitoring, such as aerial surveillance, gas monitoring, and sample collection [11], [12], [13], [14].

Studies have shown several methods in disaster monitoring and prevention using drones [15], [16], [18], [19]. These methods have shown important data in predicting and forecasting potential risks caused by disasters. The persistence of drones has the potential to resolve issues like inaccessible environments for testing and location. Thus, the utilization of drones in water sampling collection has emerged as an innovative and efficient approach, which offers significant advantages over traditional sampling methods.

Utilizing automatic samplers is a technique to obtain a more comprehensive understanding of water quality variations over time [17]. Several studies employed drones for water sample collection, utilizing pumps and tubes to collect

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FIGURE 1. Actual image of drone-based automatic water sampling system.

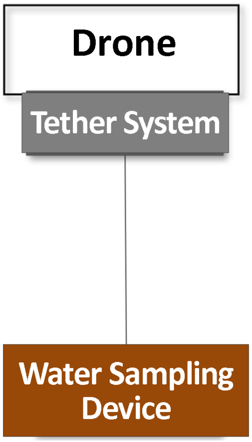


FIGURE 2. The conceptualization of drone set-up with the water sampling device attached to the drone through the tethering system that allow lowering and raising of the device.

water samples ranging from 20 mL to 100 mL [6], [20]. The advancement of the UAV-assisted water sampling system that incorporates autonomous drone operation resulted to an average of 130 mL of water sample collected, thus provides an advantage for the sampling time in using drones [21].

A study undertaken in Japan [22] used a sampling device with a capacity of 330 mL to collect water samples in a volcano crater lake and is suspended from a 30-meter length of rope, enabling the collection of less than 250 mL of water sample without using a pump. A study by [23] presents an aerial water sampler using vials through tubes integrated with the concept of flushing.

In flushing, water is flushed through the tube once for 20-second to clean it, and then proceeds to pump the water sample to be stored in the vials. A previous study [24] applied an automatic water sample collection with the auto-lock mechanism. However, in this approach, hindrances such as the use of ropes and wires endangers the sampling device during the process of collecting water sample. The present UAV-based remote water sampling devices are unable to repeatedly rinse the containers holding the samples. Moreover, previous study conducted automatic lowering and raising the water sampling device in a set-up without the drone, and gathered water sampling data of water in a steady state condition.

Thus, in this study, the developed water sampling device with an automatic lock mechanism is integrated to the drone to perform real-world scenarios of water sampling, as shown in Fig. 1. We evaluate the sampler design by conducting different test scenarios in steady state and disturbed state of water. Moreover, the tether unit (tether system) is added that will allow raising and lowering of the water sampling device installed onto the drone. A waterproof compartment for the microcontroller, battery, and Bluetooth module for collecting data and transmitting it to the drone's tether unit are added as well in the overall assembly. The spool unit or tether unit is attached to the drone, while the waterproof compartment is installed above the water sampling device.

The proposed system incorporates an automatic lock mechanism, which activates after performing field quality control to collect the necessary water sample. This study highlights the application of automating field quality control to effectively implement automatic sample collection using drones. After the water sampling device underwent a triple washing process, researchers securely sealed it to ensure the integrity of the collected water. Fig. 2 depicts the general set-up, comprising the water sampling device, tether system, and drone.

II. THE TRADITIONAL AND DRONE-BASED METHOD OF WATER SAMPLING

Traditional approach of water sampling employs divers, boats, or ropes to manually gather data, thus involves potential risks to personnel, especially in hazardous or challenging environments. The commercially available horizontal Van Dorn bottle is an example of a water sampler. The Van Dorn water sampler design ensures a representative water sample for any specific depth. However, operators are required to trigger the locking system of the water sampler. Furthermore, several steps are required in water sample collection to avoid contamination. This can require a lot of work and time, particularly for larger bodies of water. Moreover, it requires physical presence at each location and is constrained by the accessibility of the sampling sites. For cost considerations, it may result in increased expenses since more personnel, boats, and equipment are required. And costs may rise as sampling locations become more complex.

Drone-based method covers wide areas since drone fitted with the water sampling equipment allows distant sampling, thus requiring less human labour. This provides a more thorough understanding of other water body by covering difficult-to-reach places or dangerous locations such as volcano crater lakes. Drones offer the potential to fulfill various stages of real physicochemical water sampling, allowing for efficient and cost-effective data collection in extensive water sampling efforts [25], [26], [27], [28]. Previous studies utilized drones in monitoring, debris flow simulations, mapping and sample

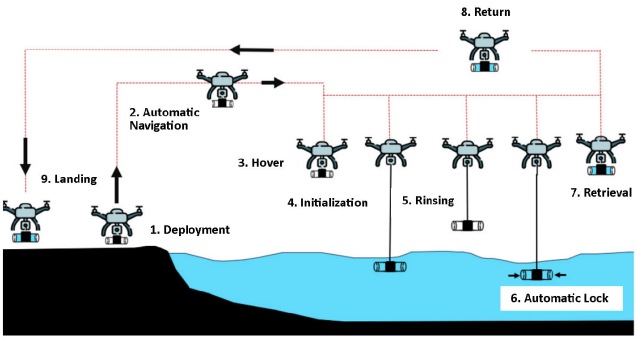


FIGURE 3. **The general concept of water sampling with autonomous navigation of the drone.**

collection. This advancement influenced the areas in remote sensing, relay communication, and acquiring samples and close observation in harsh and risky environments [1], [29], [30], [31], [32].

Using drone for water sampling can employ automated systems such as autonomous navigation to the area or location of sampling. In terms of cost, drones and sampling equipment may have higher initial set-up costs, but over time, especially for frequent and large-scale sampling, operating costs may decrease. Consequently, manual sampling can disturb the aquatic environment and contribute to contamination. While using drone for water sampling reduces environmental impact and lowering the risk of contamination because of the collection of samples without direct contact with the water. The utilization of drones in water sampling collection offers more significant advantages over traditional sampling methods.

III. FIELD QUALITY CONTROL IN WATER SAMPLING

In this study, the most important consideration for water sampling is the field quality control. The process of collecting and analyzing water samples from the natural environment involves multiple stages that have the potential to influence the observed results as presented by [3]. In the context of water sampling, field quality control refers to the set of practices and measures implemented to ensure the accuracy, reliability, and representativeness of water samples collected from various field locations. It involves rigorous monitoring and control of various factors that may affect the quality and integrity of the samples throughout the sampling process [5]. Field rinsing is a form of field quality control that involves rinsing the water sampling device 3 times to minimize contamination. Spot (bottle) sampling is the prevailing approach for measuring chemical pollutant levels in all three monitoring modes [17]. Subsequently, extraction and instrumental analysis are utilized.

Surface waters are typically sampled by directly filling the sample bottle. However, for deeper water layers below approximately 0.5 meter, this approach becomes impractical, necessitating the use of specialized water samplers. These samplers are lowered while open on a rope or steel cable and can be remotely triggered to close. Alternatively, another option is to employ pumps for sampling. Using automatic samplers is one method to acquire a more comprehensive understanding of water quality variations over time.

In this study, field quality control was also integrated through an automated water collection method. While previous studies have covered water sample collection via drones, this research introduced an innovative concept of incorporating automated application of field quality control. Fig. 3 outlines the general process of water sampling with the autonomous operation of the drone. The water sample collection commences with the deployment of the drone. Which autonomously navigates to a predetermined target location. The drone hovers and initiates an automated rinsing and auto-lock mechanism as part of the field quality control procedure. The study performed a rinsing sequence through a spool unit system by winding and unwinding the tether. After a programmed number of rinsing, the auto-lock mechanism of the device was activated, sealing the water sample inside. Following this, the drone navigates back to the ground station. The research team concludes the operation by retrieving the water sampling device.

In this study, we introduced the system design and mechanism and the device is subjected to rigorous testing to evaluate its performance. Lock test, seal test, and rinse tests were implemented. The lock test and seal test were conducted simultaneously. Successful operation was made for testing the automatic lock mechanism and successfully contained large volume of water sample with negligible leakage. We implemented an actual field test with autonomous operation of the drone - water sampling device set-up. The integration of the drone, motor spool system, and water sampling device provided a robust and efficient solution for collecting water samples, thereby facilitates scientific investigations and ensures accurate data collection.

IV. DESIGN REQUIREMENTS

This section discusses the design requirements for selecting the drone, the required tether system, and the proposed water sampling device. The wireless communication between the ground station, drone, and water sampling device is also considered.

A. DRONE SELECTION

The water sampling device is integrated to the drone, thus the availability of payload information of the drone played a critical role in drone selection. Table 1 provided an estimation of the payload information for various components, such as the water sampling device and tethered system. This data served as a basis for determining the appropriate drone for the task. After estimating the weight of the possible components and system payload, proper selection of the drone can be made.

To carry out the objectives, the selection of the drone involved fulfilling several requirements. These requirements encompassed several critical factors, including:

TABLE 1. Estimated weight allocation.

Component	Estimated Percentage (%)
Drone	35
Tethered System	35
Water Sampling Device	10
Allowance	20

1) Flight time
2) Range and Control
3) Payload capacity
4) GPS and navigation features

Flight time was a critical consideration for the researchers. A drone that could offer an adequate duration of flight to facilitate extended operations without frequent battery changes was sought. In addition, the researcher emphasized the importance of a drone with commendable range and control capabilities. The range of communication for the water sampler and the operator should consider different types of bodies of water. Volcano crater water sampling is the farthest location of sampling required with a minimum of 1-kilometer distance from the base station or where the drone operator is located. We used a drone that could fly considerable distances from the controller while maintaining a robust and stable connection. Payload capacity was another key requirement that influenced the decision-making in the selection process. The researcher needed a drone that could comfortably carry the necessary equipment specific to their applications Furthermore, the presence of GPS and navigation features held great significance for the researcher. Drones equipped with advanced GPS-assisted flight capabilities and return-to-home functions were considered. Lastly, battery life played a significant role in the drone selection. A drone with sufficiently long-lasting battery to support the intended operations is needed.

B. WATER SAMPLING DEVICE DESIGN CONSIDERATION

In harsh and risky environments, such as in volcano crater lakes with normal temperature of 50 degrees Celsius, long range communication is a challenge. According to PHIVOLCS (Philippine Volcanology and Seismology), the water sample must be up to 500 mL. Thus, the overall design requirements for the sampling device should be:

1) able to withstand water high temperatures
2) lightweight and easy to fabricate
3) water sample is visible
4) ensure minimal leakage
5) can collect up to 500 mL of water
6) orientation that allow proper washing of device and water collection

Traditionally, personnel assigned in getting the samples will wash the bottle and cap 3 times before getting the final water sample and seals it. This method is common to water sampling to ensure field quality control. Thus, the water sampling device should be sealed so no water is leaked and exposed during its sampling operation.

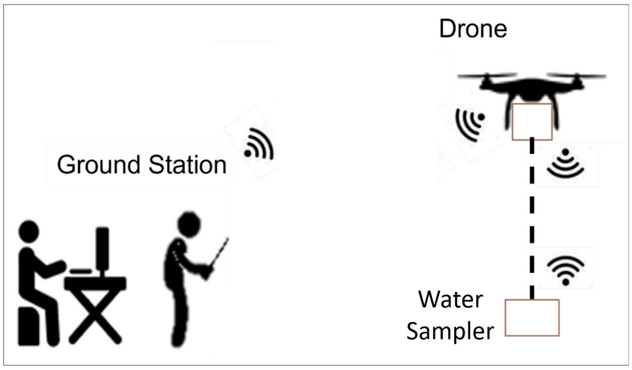


FIGURE 4. Wireless communication between ground station, drone and water sampling device.

The orientation of the water sampler should allow easy rinsing or washing of the water sample bottle 3 times before collecting the water sample. This orientation would prevent the water sampling device from water leaking.

C. TETHER SYSTEM DESIGN CONSIDERATION

In this study, the water sampler device is suspended using a line tethered to the drone. To prevent being interrupted by wind and other obstacles during the mission, the line used to hold the container should have a tether system that allow winding and unwinding of the tether line. This method allows descending and ascending motion of the water sampler. The tether system should follow field quality control by requiring the container to be washed 3 times, thus a limit switch is needed to send and return the data when the water sampling device is immersed in water. This will allow winding and unwinding of the tether line automatically. The sensor component should also ensure that water sample is collected before fully locking the water sampling device.

D. WIRELESS COMMUNICATION CONSIDERATION

The microcontroller and other components for the wireless controls of the water sampling device should be securely stored in a waterproof compartment box. A motor mechanism will be installed to control the releasing and pulling of a spool of line/cable (of the tether unit). In order to raise up or raise down the water sampling device that is attached to the end of the line/cable, a wireless transceiver must be installed on the motor mechanism for wireless communication.

A microcontroller is needed to control the motor mechanism in which pins from the drone flight controller are connected. For controlling the tether unit, manual control by the use of the remote controller can be made by attaching an onboard camera to the drone. This allows the operator from the ground station to view the water sampling process. The wireless communication is depicted in Fig. 4.

V. THE DEVELOPMENT PROCESS OF AUTOMATIC WATER SAMPLING DEVICE

In this study, conducting data collection initiated the first phase of developing the water sampling device to identify

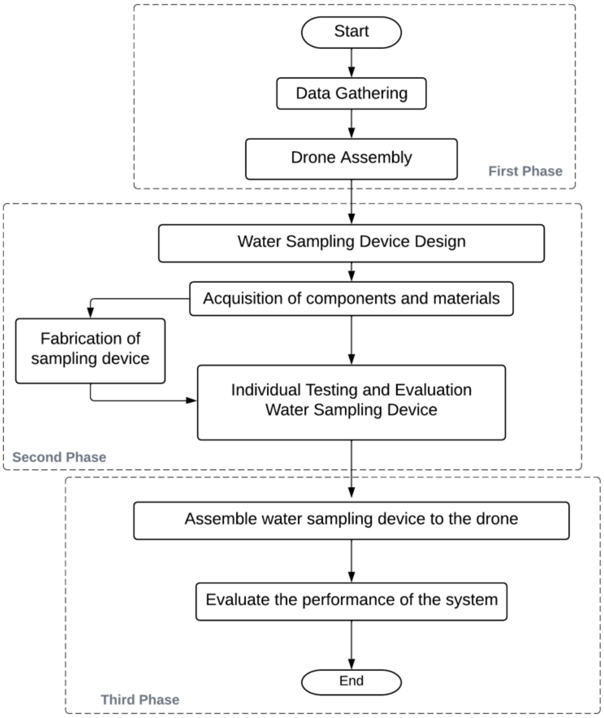


FIGURE 5. The development process of drone-based water sampling device.

the required parts and components., as illustrated in Fig. 5. Following that, we undertook the drone assembly process, taking into account the weight of both the payload and the drone.

The second phase of the study began with the initiation of planning and design for the sampling device. Subsequently, the fabrication process was undertaken to create the components of the water sampling device. Additionally, we carried out the design and procurement of parts for the sampling devices in conjunction with the fabrication process. We conducted individual testing and evaluation for the water sampling device to establish and monitor specific parameters prior to integration. The integration of the drone and the water sampling device concluded the final phase of the study.

In the final phase, we conducted testing and evaluation of the developed water sampling device. After testing the individual parameters needed for the water collection method, we then tested and evaluated the drone and water sampling system in an open water environment.

A. WATER SAMPLER DESIGN AND CONCEPTUALIZATION

As proposed in the paper, the system includes the following: the drone, a tether unit or tether system, and a water sampling device. The tether unit has a tether wound around a spindle coupled to a DC motor, which is affixed to the drone. The DC motor is responsible for the winding and unwinding of the tether that allows raising and lowering of the water sampling device from the drone. We attached the water sampling device to the free end of the tether.

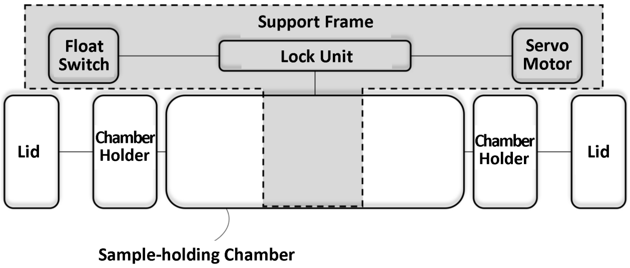


FIGURE 6. The design concept for the automatic water sampling device and its components.

In Fig. 6, the researcher purposely designed the water sampling device with a horizontal orientation. The chamber holders hold the ends of the sample-holding chamber and have openings such that, when the lids are detached from the said openings, water freely enters and exits the chamber. To seal the water sample inside the sample-holding chamber, we configure the lids to attach to the openings of the chamber holders. A float switch is used and located above the sample holding chamber. When the float switch makes contact with the water surface, it sends a triggering signal to the microcontroller connected to the DC motor and causing the tether unit to wind and unwind. The servo motor is attached with an arm in contact with the lock unit. This servo motor serves as an actuator to lift the lock unit causing the lids to attach to the openings of the chamber holders.

B. AUTO-LOCK MECHANISM

The water sampling device consists of a tube, in-tube springs, auxiliary springs, shafts, a lock trigger unit, and a servo motor, as conceptualized in Fig. 6. We arranged the tube springs side by side such that the adjacent ends are fixed and attached to the tube at its middle, while the other free ends point towards the opening of the tube along its longitudinal axis. Each of the shafts has one end attached to the free end of an in-tube spring and the other attached to the corresponding lid.

The tension applied by the in-tube and auxiliary springs provides the force to attach the lids to the chamber holder, as illustrated in Fig. 7 and 8. The F_{S1} is the force exerted by the in-tube spring, while F_{S2} is the auxiliary spring force that is supporting the motion of the F_{S1} to be in the same direction prior to closing. The F_{S1} is the main spring that creates the tension and where the lock trigger unit is inserted to hold the chamber lid open still, while the F_{S2} supports its direction. This means that the spring force to be designed is the F_{S1}, noted that F_{S1} is greater than F_{S2}.

$$F_{S1} > F_{S2} \tag{1}$$

$$F_{S1} = -kx \tag{2}$$

where k is the spring constant and x is the distance displaced by the in-tube spring.

The maximum tension force from the two springs is from the in-tube spring, of where the lock trigger unit's shaft will be

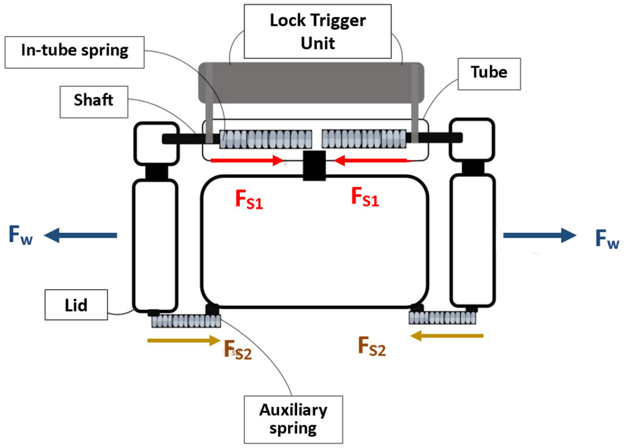


FIGURE 7. **The state of the water sampling device prior to closing. In this state (unsealed sample-holding chamber), the lids, detached from the chamber holders, pull the shafts towards the openings of the tube along its longitudinal axis. This subjects the in-tube springs to stretching forces that are not relieved due to the lock trigger unit pressing or holding on the shafts. F_{S1} is the force exerted by the in-tube spring, F_{S2} is the force exerted by the auxiliary spring, and F_W is the force exerted by the water surrounding the lid.**

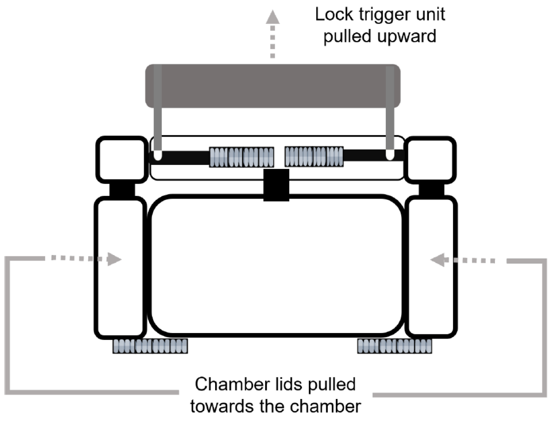


FIGURE 8. **The state of the water sampling device after closing. In this state (sealed sample-holding chamber), lifting the lock trigger unit causes the breaking contact from the shafts. This allows the in-tube springs to expend the stored energy via retraction, pulling the shafts and attaching the lids to the water sampling device's chamber holders.**

inserted to hold the chamber lid in place (in open state). Thus, F_{S1} needs to be greater than the force exerted by the water, F_W, on the sampling device. To find these forces Eq. (1), Eq. (2), and Eq. (3) were used.

$$F_W = \rho g h A \tag{3}$$

where ρ is the water density, g is the gravity, h is the depth from water surface, A is the surface area of the sampling device.

With the condition $F_{S1} > F_W$, the minimum spring force is the value of the force exerted by the water. Therefore,

$$F_{S1} = F_W \tag{4}$$

$$-kx = \rho g h A \tag{5}$$

$$k = \frac{\rho g h A}{x} \tag{6}$$

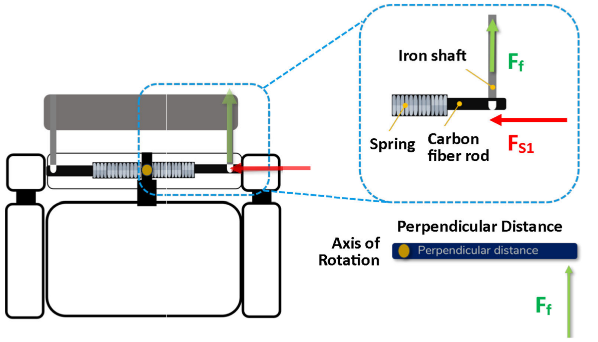


FIGURE 9. **The torque and frictional force parameter of the water sampling device. Torque is determined using the perpendicular distance from the point of contact of the servo motor arm and the horizontal beam of the lock trigger unit as the axis of rotation and the frictional force caused by the iron shaft, carbon fiber rod, and spring.**

After finding the spring constant from Eq. (5), we can identify the spring to be used in the lock trigger unit of the sampling device. Shaped as a horizontal beam with vertical protrusions, the lock trigger unit is moveable and attached through a space in the support frame. We also configured the space in the support frame to only allow the lock trigger unit to move vertically. The vertical protrusions pass through openings in the tube to make or break contact with the shafts.

As illustrated in Fig. 9, attached to the servo motor is an arm whose upper surface is in contact with the bottom surface of the horizontal beam of the lock trigger unit. We considered the frictional force with the coefficient of friction between the carbon fiber shaft and the steel vertical protrusion to find the force on the horizontal beam.

$$F_f = \mu F_{S1} \tag{7}$$

where F_{S1} is the spring force. And to find the torque on the lock assembly, τ,

$$\tau = rF_f \tag{8}$$

where r is the perpendicular distance from axis of rotation as illustrated in Fig. 9.

VI. THE IMPLEMENTATION PROCESS OF AUTOMATIC FIELD QUALITY CONTROL

Following the design conceptualization of the water sampling device, the researchers proceeds with the automated implementation of field quality control by automatic rinsing of the device through the tether unit as shown in Fig. 10. The tether unit consists of a tether wound around a spindle coupled to a DC motor. The DC motor turns the spindle one way to unwind the tether and the other way around to wind the tether. The water sampling device is attached to the free end of the tether. Thus, by winding and unwinding the tether, and letting the water in and out of the device, the device can rinse itself.

To achieve automatic rinsing and collection, we programmed the microcontroller to allow 3 cycles of repeated dipping and raising of the sample-holding chamber. During this process, the lids are kept detached from the chamber

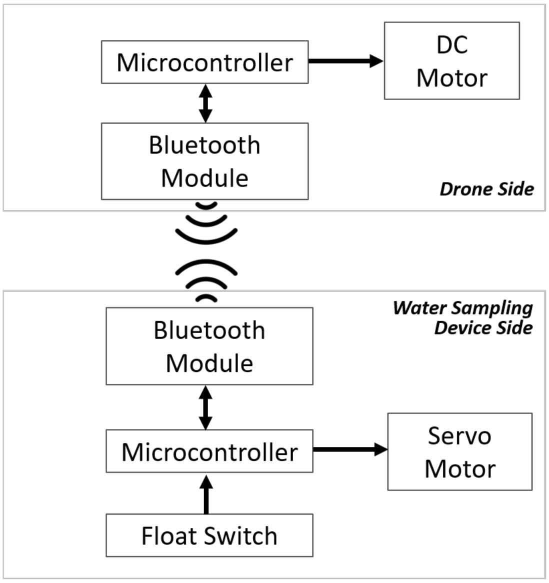
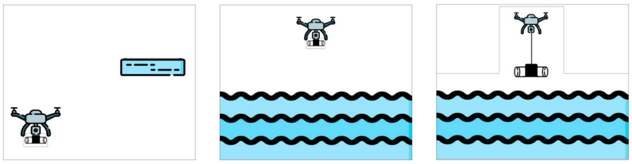
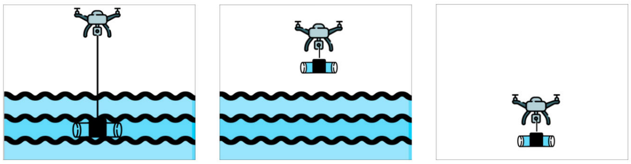


FIGURE 10. The connection diagram of the water sampling device and the drone side with the tether unit.



(a) Deployment (b) Hovering (c) Initialization



(d) Rinsing (e) Auto-lock (d) Retrieval

FIGURE 11. The multi-step water collection process, started with system deployment (a), and once a target location was designated the drone navigated autonomously and hovered at a specified height (b) to initiate water collection by unwinding the tether (c). The system automatically applied field quality control by rinsing (d) and locking the sampling device (e), and finally, the device goes back to the base station and is retrieved (f).

holders. Before raising in the final cycle, the lids are attached to the chamber holder, sealing the water sample in the sample-holding chamber.

The microcontroller signals the tether unit to unwind the tether (thus lowering the support frame) and dip the unsealed sample-holding chamber. This allows the water to fill the sample-holding chamber. Moreover, the microcontroller signals the tether unit to wind the tether (thus raises the support frame) for a user-defined duration to release at least some of the water from the unsealed sample holding. This process of unwinding and winding is repeated 3 times. The float switch guides the timing of the microcontroller. The microcontroller signals the tether unit to wind the tether and triggers the lock unit to attach the lids into the chamber holder of the water chamber or sample-holding chamber.

When the microcontroller signals the lock unit to attach the lids, the servo motor turns through an angle enough to cause the arm to lift the lock trigger unit such that its vertical protrusions cease to be in contact with the shafts. This allows the pulling and attaching of the lids to the chamber holders.

VII. PERFORMANCE EVALUATION AND METHODS

This section discusses the methodologies of lock, rinse, and seal testing for the water sampling device, and actual field testing for drone-based water sampling system. We evaluated the proposed drone-based water sampling system by conducting independent tests to ensure the reliability of the water sampling collection method. To achieve this objective, we performed the subsequent set of individual tests.

A. LOCK TESTING FOR WATER SAMPLING DEVICE

The water sampling device underwent a lock test, where it was immersed in a container of water. The horizontal plate of the lock trigger unit was then manually lifted. The trigger mechanism was visually inspected to ensure proper operation, resulting in the lids being pulled towards the water chamber. The sampling device was raised following the visual inspection to check for any noticeable signs of leakage. After completing the test, the researcher moved on to the next individual test.

B. RINSE AND SEAL TESTING FOR WATER SAMPLING DEVICE

The rinse test aimed to assess the automated field quality control with a water sampling device attached to the tether. The tether system autonomously winds and unwinds its tether, enabling the water sampling device to touch the water 3 times. The device is then locked after rinsing it 3 times. The test concluded with the retrieval of the water sampling device by retracting the tether, signified by the triggering of the limit switch in the tether unit to stop the process.

After securing the water sampling device, a seal test was performed. The container was suspended for half an hour with an empty basin under it to gather potential leakage. The water sampling device underwent a visual inspection, and after the designated time had elapsed, the amount of water inside the device was measured.

C. OPEN WATER ENVIRONMENT TEST SET-UP FOR WATER SAMPLING DEVICE WITH THE DRONE

With the water sampling equipment integrated to the drone, practical testing in an open water environment allows autonomous operation of the drone alongside the water sample device. To ensure a secure flight, a comprehensive pre-flight checklist was completed. The multistep water collection process, outlined in Fig. 11, starts with system deployment. Before deployment, drone setup evaluation and flight plan validation was done. Once a target location is designated and GPS parameters are set, the drone navigates

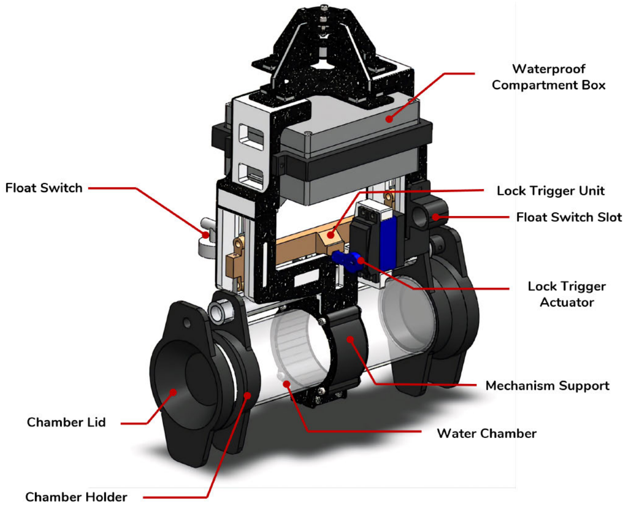


FIGURE 12. **The 3D model of the water sampling device consists of a mechanism support, lock trigger unit, float switch slot, and the main water chamber.**

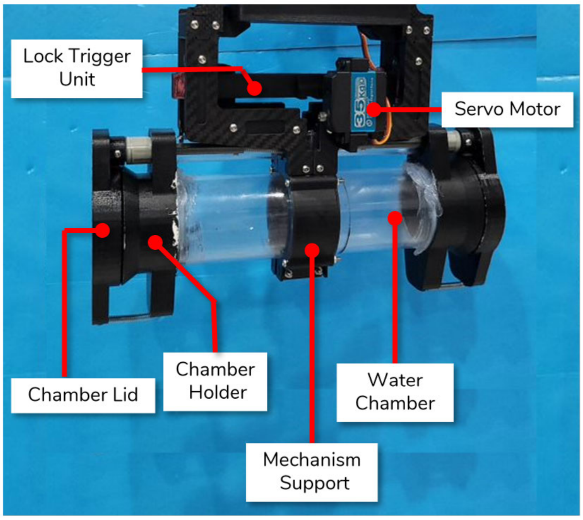


FIGURE 13. **The actual water sampling device showing the main water chamber, mechanism support, servo motor, chamber lid, chamber holder, and lock trigger unit.**

autonomously and hovers at a specified height to initiate water collection by unwinding the tether. The system automatically applies field quality control by rinsing and locking the sampling device. Subsequently, the researcher retrieves the water sampling device and facilitates the collection method.

VIII. DEVELOPED WATER SAMPLING DEVICE

A. FABRICATION AND ASSEMBLY

The water sampling device features an acrylic tube as the main water chamber which is securely positioned within the support frame, as shown in Fig. 12 and 13. Apart from the acrylic tube, the support frame accommodates the lock trigger unit, lock trigger actuator (comprising a servo motor), float switch, and a waterproof compartment box (comprising the microcontroller, battery and Bluetooth module).

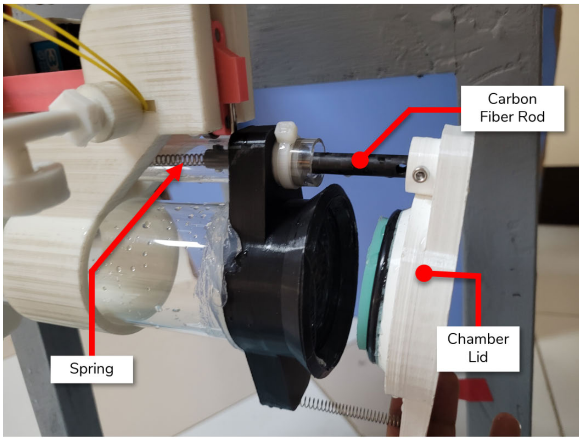


FIGURE 14. **The chamber lid attached to the carbon rod connecting the main spring. A guide spring was used and attached between the chamber holder and chamber lid.**

The microcontroller, battery, and Bluetooth module are housed within the waterproof compartment box, collecting data from the float switch and transmitting it to the DC motor in the drone's tether unit. To ensure the presence of water in our sample holding chamber, the researchers incorporated a float switch into the device. This assembly of waterproof compartment box gave a total weight of 814 grams.

A metal arm is attached to the servo motor that is in contact with the horizontal plate of the lock trigger unit. The lock trigger unit features two vertical protrusions at both ends, inserted into a carbon fiber shaft. Lifting the lock trigger unit releases the tension from the spring, causing the lids to close. Thus, the fabricated and assembled water sampling device has a total weight of 1,318 grams. The maximum water sample that the fabricated water sampling device can collect is up to 531.5 mL (531.5 grams).

B. LOCK TRIGGER UNIT ASSEMBLY

The lock unit included a set of springs as shown in Fig. 14. The researchers utilized springs to apply tension to the chamber lids. Thus, these springs were inserted into tubes incorporated within our support frame to stabilize them. The primary springs, called in-tube springs, provide tension to the system. The other set, called auxiliary springs, is placed beneath the lids and chamber holders to guide and ensure the proper closure of the device.

In reference to Eq. (5), the spring to be used was identified using the ρ value of 997 kg/m^3 and h of 0.10 m. The area is equal to πr^2, where r is the radius of the container.

Two pairs of springs were considered. The spring constant calculated is 0.2407 mm for the in-tube spring. A closed extension spring with dimensions of 0.7 mm wire diameter, 5 mm outer diameter, and 30 mm length inside the loop was used in the system. This spring has a spring constant of 0.9049 N/mm. For the guide spring located at the bottom of the chamber lid, it must satisfy F_{S1} is greater than F_{S2}, where F_{S1} is the force exerted by the main spring, and F_{S2} is the force exerted by the guide spring.

The available spring for guide spring, which is the auxiliary spring, is a closed extension spring with dimensions of 0.5 mm wire diameter, 5 mm outer diameter, and 30 mm length inside the loop. This spring has a constant of 0.1509 N/mm. Using Eq. (1) and Eq. (2) and the values of the parameters mentioned gave F_W equal to 2.407 N, F_{S1} equal to - 9.049 N, and F_{S2} is equal to - 3.018 N.

Taking the magnitudes of the forces, the force exerted by the springs is greater than that of the water. Thus, when the assembly lock lifts the shafts, it releases the spring from its tension and pulls the chamber lid towards the chamber holder. An O-ring and cured molded silicone are fixed to the chamber lid to ensure little to no leakage when the sampling device is closed. To find the servo motor to be used, the torque on the lock assembly was solved. Friction force on the steel and the carbon fiber is considered with the coefficient friction of 0.14. The frictional force is equal to 1.27 N, as computed using Eq. (7). The torque at the lock assembly can be acquired considering the utilization of two steel shafts. Setting the safety factor to 2.5 [33], Eq. (8) gives the value of the torque to 0.505 Nm.

The selected servo motor has a rating of 3.4335 Nm. Since $\tau_{motor} > \tau_{lock}$, the motor was able to lift the lock assembly having the chamber lid pulled towards the chamber holder.

IX. DEVELOPED DRONE-BASED WATER SAMPLING SYSTEM

In this study, the components of the water sampling device was introduced in Fig. 12 and 13, which includes the water chamber assembly, float switch, lock trigger unit, lock trigger servomotor, and the waterproof compartment box. The microcontroller, battery and Bluetooth module is housed inside the waterproof compartment box. The water chamber component serves as the main container of the water sample. The mechanism support holds the water chamber, lock trigger, lock trigger actuator, and float switches. The float switch serves as indicator if the container is submerged in water. The lock trigger unit includes shafts on both ends to hold back the springs attached to the chamber lid. The lock trigger actuator includes servo motor that is programmed to activate at a certain angle to lift the lock trigger unit. The chamber lid seals the water inside the water chamber, and the waterproof compartment box seals the battery, microcontrollers and the wireless communication device. The float switch used is a right angle water mini-float switch, and the actuator for triggering the lock unit is a servomotor with 35 kg-cm rated torque based on the calculated servo motor rating in section VIII-B.

A. DRONE PAYLOAD AND SPECIFICATIONS

Drone payload calculations includes actual weight of the components based on the availability and design requirements discussed in Chapter IV. Table 2 summarizes the components needed in this study for drone payload consideration. It was found that the maximum total payload from the actual components was 4,376 grams. In order to carry the 2,727.5 grams (2.7275 kg) payload, the researchers utilized a high payload octocopter drone with maximum take-off weight of 10 kilograms.

TABLE 2. Summary of drone payload calculation.

Component	Subcomponents	Weight (grams)
Water Sampling Device	Water Chamber Assembly Float Switch Lock Trigger Unit Lock Trigger Servomotor Waterproof Compartment Box (Microcontroller Battery and Bluetooth Module)	1318
Tether System	Tether (Spool Unit) DC motor Limit Switch Component Holder	878
Water Collected		531.5
	Total Payload	
	Without Water Collected	2196
	With Water Collected	2727.5

TABLE 3. Drone components and its payload (considering max. take-off weight).

Component	Specifications	Weight (grams)
Payload	Water Sampling Device Tether System Water Collected Other Components	2727.5
Drone Assembly (Octocopter)	10-kilogram Maximum Take-off Weight (MTOW) X8 T1000 Frame with Tarot 1555 Propeller, PX4 Flight Controller, and H-RTK-F9P Helical GPS	4545
Drone Battery	10000 mAH 6S battery	1438

Table 3 summarizes the drone components and its specifications, and the total payload. To minimize costs, the researcher assembled the drone using individually purchased parts. The octocopter, with a Tarot X8 T1000 frame, Tarot 1555 propeller, Pixhawk Cube PX4 flight controller, RTK GPS, and required battery of 10,000 mAH. Moreover, its maximum power consumption is 4,000 Watts; thus its hovering power consumption for 7-minute hovering time is 1,500 Watts at 9.5 kilograms using 10000 mAH battery.

The drone assembly with battery has a total weight of 5,983 grams. Its payload include communication unit, tether system, water sampling device, and other components. The communication unit is SIYI HM30 Long range Full HD Transmission System with Remote control, telemetry, and video transmission function. Thus, the total

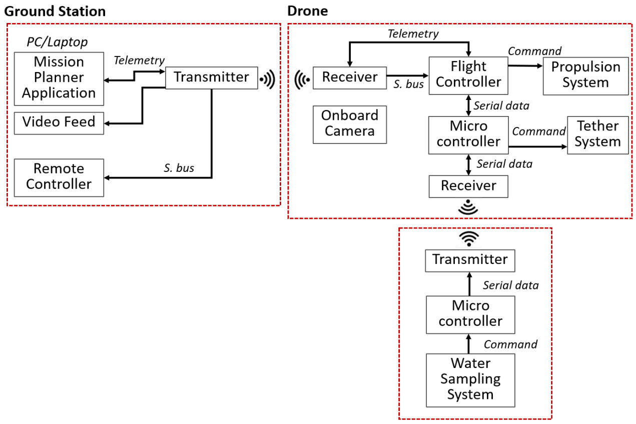


FIGURE 15. The overall control diagram for the wireless communication of the ground station, the drone, and the water sampler.

weight of the water sampling device and drone set-up is 10.36 kilograms.

B. THE WIRELESS COMMUNICATION SYSTEM

Fig. 15 shows the overall control diagram for the wireless communication of the ground station, the drone, and the water sampler. The ground station and the drone are communicating directly for remote control, mission planner application and video feed. The drone and the water sampler are communicating directly for the data acquisition. Communication unit consist of SIYI HM30 Long range Full HD Transmission System with remote control, telemetry, and video transmission function.

The ground station is where the operators stay during operation. The personal computer (PC) or laptop shows the Mission Planner application and the video feed that provides the drone status and visual data. The Mission Planner application helps pilots and operators to plan the execution of operations. It provides information about the unmanned aerial vehicle (UAV) and the water sampling device at the ground control station. The remote controller is used to control the drone and also the tether system which is attached to the drone. The PC and remote controller are connected to a transmitter (SIYI Ground Unit) which sends to the receiver (SIYI Air Unit) that is attached to the drone.

The main component for the drone is the flight controller which relays commands from the ground station to the propulsion system and the microcontroller. The flight controller and the onboard camera are connected to the receiver (air unit) to send video feed and drone data to the ground station. The microcontroller is used to command the tether system for lowering and raising the load or water sampling system that is attached to the drone. A receiver (bluetooth) is used to connect to the transmitter (bluetooth) in which the data received is the basis for the action of the tether system. Lastly, the water sampling system comprises a Bluetooth transmitter and a microcontroller. Each step of the process of the water sampling system gives a specific command and is transmitted to drone side which determines the action of the tether system.

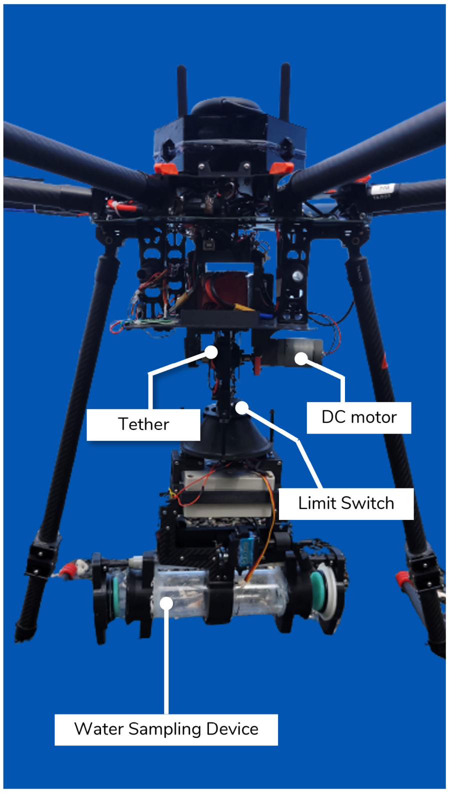


FIGURE 16. The actual water sampling device attached to the drone with the tether system.

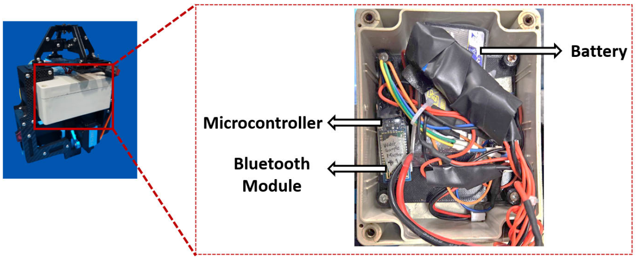


FIGURE 17. The actual waterproof compartment box with microcontroller, battery and Bluetooth module inside.

C. DRONE AND WATER SAMPLING DEVICE SET-UP

After assembling the water sampling device, it was installed onto the drone. The system incorporated into the drone set-up comprises the drone itself, the tether system, and the water sampling device. Fig. 16 shows the actual overall system of drone-based automatic water sampling device.

The waterproof compartment box shown in Fig. 17 contains the control system circuit of the water sampling device. The compartment has microcontroller (Arduino Nano), a wireless communication device (Bluetooth module), DC-DC converter, and the 7.4 volts battery to power both the Arduino Nano and the servo motor. A waterproof box was modified to fit the components and seal it to protect it from water during testing.

Consequently, the distance from float switch to the lower part of the water sampler tube is about 101 mm. Thus, this also corresponds to the maximum depth from the water level

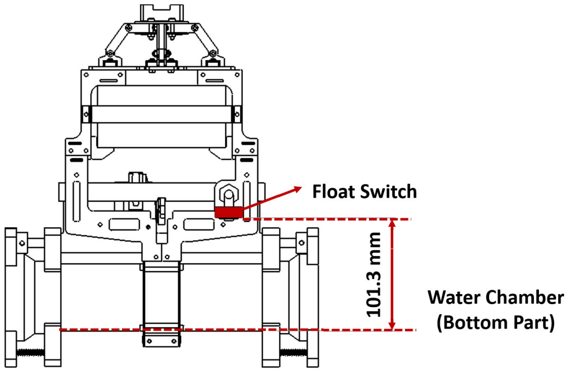


FIGURE 18. **The distance from float switch to the bottom part of the water sampling device's chamber, which correspond to the maximum depth of water of water sampling.**

from where the samples were collected. Fig. 18 shows the location of the float switch relative to the water sampling device's water chamber (where the water sample is collected).

D. INTEGRATED FIELD QUALITY CONTROL

The entirety of the flight mission including the water collection method and the application of field quality control is set to be autonomous. The control system of the rinsing and water collection method of the water sampling device was summarized as follows:

1) The tethered system which includes the DC motor extended the line holding the water sampling device
2) When the float switch detected the water and turned on, it sent a signal to the DC motor.
3) The DC motor was prompted to retract the line for about 5 seconds as programmed and then extended again until one of the float switches was turned on. The process of extending and retracting of the line was repeated thrice to apply field quality control procedure.
4) After the process of rinsing was executed, the automatic locking was commenced after the fourth dip of the water sampling device in the water. After recording the data that the sampling device completed the rinsing process, the float switch prompted the servo motor to lift the lock trigger unit releasing the tension of the springs holding the chamber lid. As a result, the water sample was sealed and locked inside the water sampling device.
5) For the retrieval of the device, the DC motor retracted the line. In the tethered system, a limit switch was triggered to direct the DC motor to stop retracting the line.

X. RESULTS AND DISCUSSION

A. LOCK TEST ASSESSMENT OF THE WATER SAMPLING DEVICE

The initial testing of the automatic lock mechanism was performed manually. The water sampling device was suspended using a tether, and a basin of water was placed beneath it. The researcher submerged the water sampling device in the water and then manually pulled the lock trigger unit to release the tension from the spring, causing the device's chamber lid to close and seal the water inside as shown in Fig. 19.

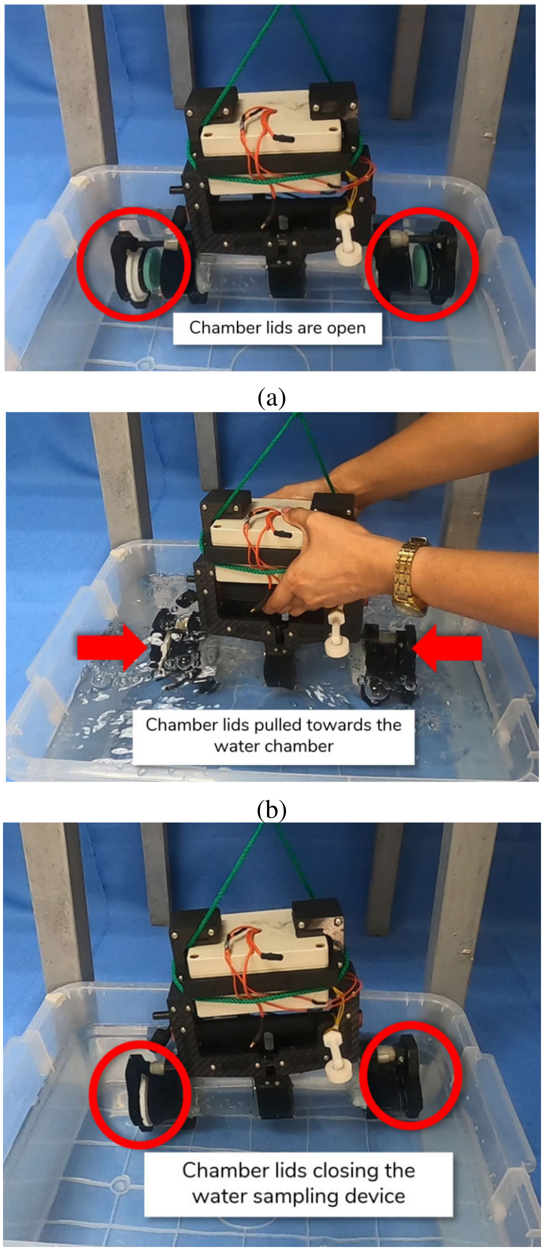
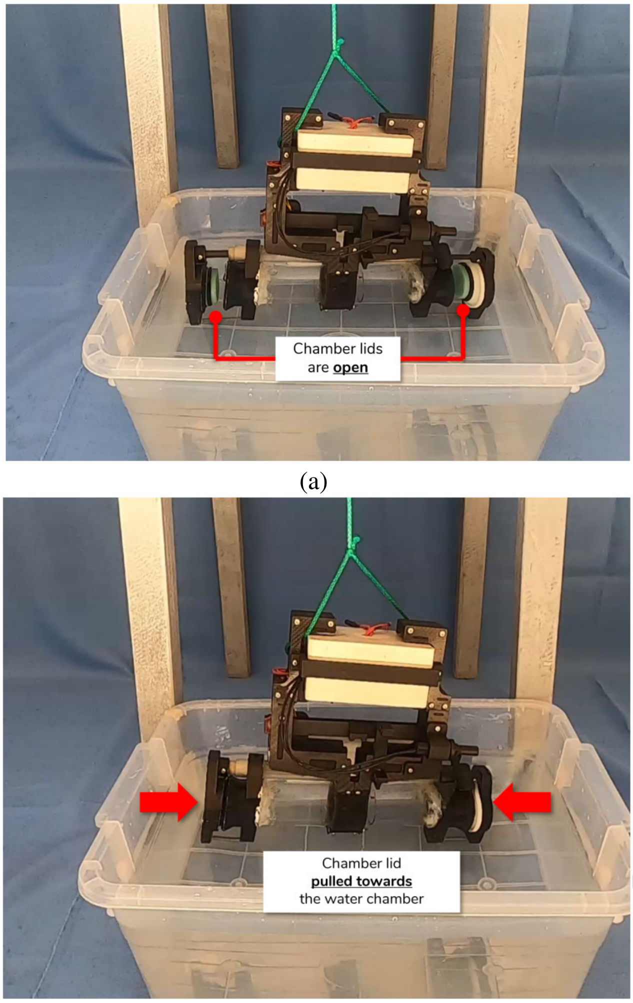


FIGURE 19. **The water sampling device during its locking test performance investigation. The chamber lids are open indicating the state before locking (a), then manual triggering is made to assess the automatic locking of vice (b), and the chamber lids successfully closed (c).**

B. SEAL TEST ASSESSMENT OF THE WATER SAMPLING DEVICE

The water sampling device underwent rigorous testing to evaluate its performance. The lock and seal test were conducted simultaneously. Following locking using the remote controller, the water sampling device was suspended



(a)

(b)

FIGURE 20. The water sampling device during its seal test performance investigation. The chamber lids were initially open (a) and after manual locking, a 30-minute duration was made and assess the presence of any notable leaks in the water sampling device (b).

for approximately 5 minutes to allow any excess water to drain as shown in Fig. 21. Subsequently, a 30-minute timer is initiated to assess the presence of any notable leaks in the water sampling device. Throughout this examination, a dry basin was positioned beneath the device. Following a 30-minute duration, the water sample's volume was collected and quantified.

It was determined that the water sampling device could successfully hold and contain 500 mL of water for half an hour, with negligible leakage. This result ensures that the collected sample remains intact and representative of the water source under investigation. Moreover, the duration for collecting and locking the sample took 4 seconds in average. Rinsing of the water sampler 3 times only took less than 30 seconds. The effectiveness of the water sampling device's design and functionality provides confidence in its ability to perform its intended purpose reliably and efficiently.

TABLE 4. Seal test results of the device of 531.51 mL capacity.

Test No.	*Water Retained (mL)*	*Water Retained (%)*
1	529.5	99.62
2	528.4	99.41
3	521.5	98.11
4	523.7	98.53
5	524.2	98.62
6	530.3	99.77
7	523.1	98.42
8	524.7	98.72
9	527	99.15
10	530.9	99.89
11	528	99.34
12	525.3	98.83
13	523.2	98.44
14	530	99.72
15	528	99.34
16	526.8	99.11
17	529.3	99.58
18	526	98.96
19	528	99.34
20	529	99.53
21	530	99.72
22	526	98.96
23	523.3	98.46
24	529.3	99.58
25	528.9	99.45
26	526.8	99.11
27	526	98.96
28	530	99.72
29	528.1	99.36
30	524.8	98.74

C. RINSE AND SEAL TEST ASSESSMENT: FIELD QUALITY CONTROL APPLICATION

In this study, the most important consideration for water sampling is the field quality control. Field rinsing is a form of field quality control that involves rinsing the water sampling device 3 times to minimize contamination. In this study, field quality control was also integrated through an automated water collection method.

The automatic lock of the water sampler was made after 3 times rinsing was made. The test was conducted automatically as the water sampling device remains connected to the tethered system, which is, in turn, attached to the drone. A sizeable container was filled with water and positioned beneath the system, as shown in Fig. 22.

The rinse and seal test procedure consists of the following:

1) Rinsing of the water sampler 3 times
2) Collecting the water sample
3) Locking the water sampler

Simulating waves set-up condition in the container was also carried out to evaluate the float switch device's precision in transmitting data to the DC motor. A simulation of the automatic application of field quality control was displayed during testing. Three tests have been done. The system successfully performed 3 rinses on the water sampling device,

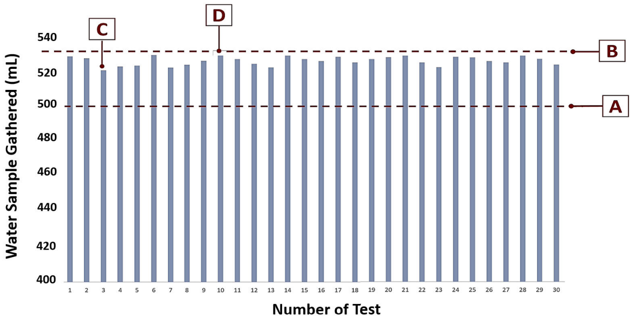


FIGURE 21. Visual representation of water gathered after 30 rinse and seal tests were conducted (simultaneous rinsing 3 times then automatic locking of the water sampler). *A* is the required volume of 500 mL, *B* is the maximum volume of the water sampling device, *C* is the minimum water gathered, and *D* is the maximum water gathered.

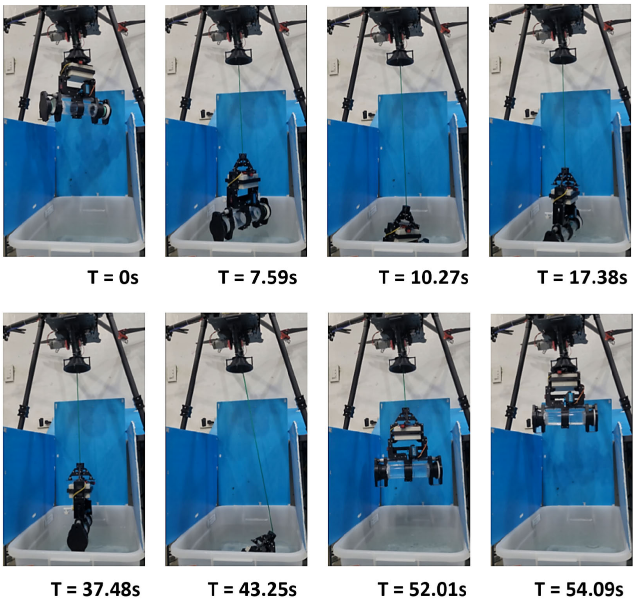


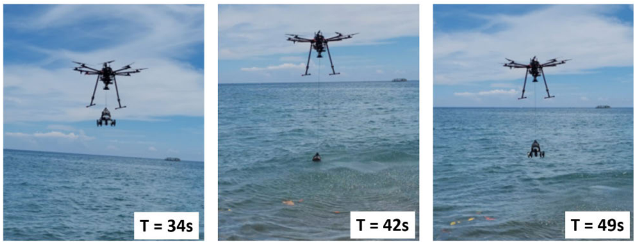
FIGURE 22. The water sampling device during its automatic rinse and lock test performance investigation with the tethered system working autonomously.

thereby implementing field quality control. Following the rinsing process, the device autonomously sealed itself and was ready for retrieval.

D. ACTUAL FIELD TEST AND EVALUATION

The drone equipped with the water sampling device underwent testing in an open water area, as shown in Fig. 23, with careful consideration given to wind speed and deployment area. The authors tested the water sampling device in the sea. It is necessary to validate the device in an open water body, which is why the sea fits to represent natural occurrences such as erratic wind gusts and sea wave conditions. The selected site has a maximum wind gust of around 5 m/s. The traditional method of water sampling in an open area such as sea employs boats and ropes to manually gather data. This can require a lot of work and time, particularly for larger bodies of water. For cost considerations, this may result in increased expenses since more personnel, boats, and equipment are required.

(a) Deployment (b) Navigation (c) Hover



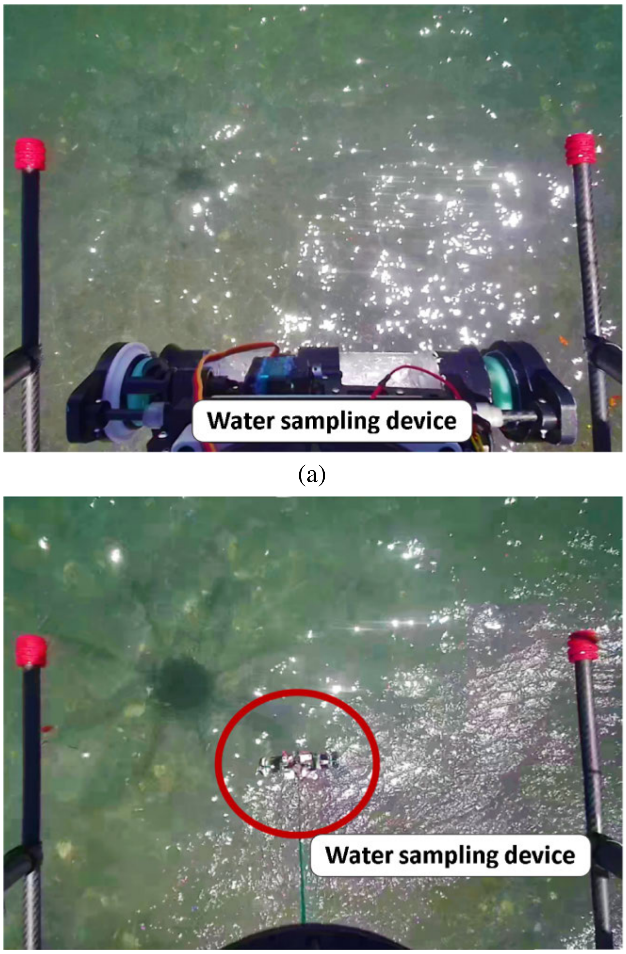
(d) Initialization (e) Immersion (f) Triple Rinsing

(g) Auto-lock (h) Retrieval (i) Landing

FIGURE 23. Actual field test of the autonomous drone-based water sampling system, involving system deployment (a), autonomous navigation of the drone (b), hovering at a specified height for water collection while unwinding the tether (c to e), automatic field quality control through rinsing (f), and securing the sampling device (g). Subsequently, the tether winding back process causes the water sampling device to return to the drone (h), and the drone returns to its base station, successfully landing on the ground (i).

Prior to commencing the test, the GPS coordinates of the target location were determined. The drone was positioned on a level surface as the starting point and then elevated to a hovering height of approximately 3 meters. Once hovering, it moved to the predefined GPS location and hovers at about 2 meters above the water surface. The water sampling collection process was initiated, which involves the winding and unwinding of the tether holding the water sampling device through the activation of the float switch. This process was repeated 3 times, followed by the automatic locking of the water sampling device after its fourth submersion, effectively sealing the water inside. The time taken in rinsing the water sampling device for 3 times took about maximum 28 seconds. The water collection and locking the sample only took 5 seconds.

Throughout the test, a camera was attached to the drone, providing close monitoring of the entire water sampling collection process. The camera captured essential details and actions, aiding in the analysis and evaluation of the system's performance as shown in Fig. 24. The presence of waves did not affect the functionality of the water sampling device, as it was able to wash itself passively and lock securely. The entire



(a)

(b)

FIGURE 24. The onboard camera view attached to the drone in which the water sampling from the drone (a) goes down to the water at 3-meter height (b), which facilitates or allows close monitoring of the complete water sampling collection process.

water collection process took approximately one and a half minutes, while the drone was programmed to hover for an additional two minutes to ensure the completion of the water collection procedure. Once the designated time elapsed, the drone returned to the ground station, which was its initial starting point, marking the successful completion of the water collection test.

The developed water sampling device is limited in the size of the water chamber in order to collect certain volume of water. Thus, the volume of water sample depends on the available size of acrylic tube (water chamber of the device). Moreover, the protective coatings and material used for the water sampling device depends on the type or condition of the environment on where the sampling is made. Thus, it is recommended to conduct regular monitoring and maintenance for the water sampling device considering the discussed limitations.

To summarize, the proposed water sampling device in this study highlights its automatic control of locking mechanism of collecting the water sample while typical water sampler such as Van Dorn water sampler, that needs manual locking of the device. Moreover, traditional water sampling such as sampling tubes usually employs divers, boats, or ropes to manually gather data, which can require a lot of work and time, particularly for larger bodies of water. Moreover, it requires physical presence at each location and is constrained by the accessibility of the sampling sites. The drone-based water sampling system in this study covers wide areas since drone fitted with the water sampling equipment allows distant sampling, thus requiring less human labor. Field quality control was performed in this study by washing the water sampling device 3 times to avoid contamination utilizing the drone tethered system. Furthermore, the automated lock mechanism sealed the water inside the water chamber and resulted in 500 mL of water collected with minimal leakage.

XI. CONCLUSION

The quantity of water samples collected, the procedure to minimize contamination, and the process to prevent leakage during water sample collection, are the major challenge of existing water sampling methods nowadays. To address the problem, a drone-based water sampling device with tethered system and auto-lock mechanism was developed.

In this study, field quality control was made through washing the water sampling device thrice to avoid contamination using the drone tethered system. Moreover, the automatic lock mechanism resulted in sealing the water inside the water chamber. With its effective design and functionality, the device reliably kept and contained 500 mL of water with minimal leakage, demonstrating confidence in its intended purpose.

The water sampling device underwent field testing in an open-water environment, following the drone autonomous operation. During the test, field quality control by rinsing the device 3 times was made and successfully gathered and sealed the water sample. This highlighted the system's applicability and effectiveness in real-world scenarios.

XII. RECOMMENDATIONS

Future efforts include field testing for versatility, optimizing sensors, improvement of the device coating application, and filtration considerations to elevate system performance and ensuring its adaptability and reliability to diverse water sources.

The durability of the water sampling device can be further investigated considering other bodies of water and extreme conditions of water, such as volcano crater lake having high-temperature and influenced by geochemical changes.

In future works, the researchers also plan to develop a reliable and durable water sampler device such carbon fiber-based holder (properties: lightweight, high strength, high temperature resistant, and corrosion resistant), and PTFE plastic water container (chemical-resistant).

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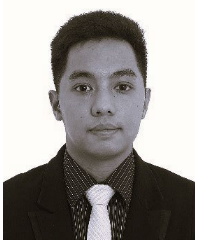

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