Design and Deployment of a UAV Mounted Autonomous Water Sampling Payload

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Abstract

Our Engineering Physics and Applied Design Capstone Project focused on developing a UAV Mounted Autonomous Water Sampling Payload. This product of this project is intended to aid researchers, such as those at the Virginia Institute of Marine Science, in collecting quality water samples with minimal resource expenditure. We developed a payload two UAVs, one of which was the Tarot 650, with a 3 pound maximum payload, and the other the Aurelia X8, with a 17 pound maximum payload. This report will detail the design process that lead up to the development and successful testing of our payload. We concluded this project with a servo-motor triggered payload mounted to the Aurelia X8 UAV, complete with an emergency release system, that is capable of autonomously retrieving a one liter surface sample of water from a designated point.

Contents

1 Introduction

Water sampling is an essential monitoring process around the world with applications in marine research, public safety, and general water quality analysis. Typically, in order to collect a water sample more than a few meters from the shore, a vessel deployment is required and a crew of at least 3 people must be involved. This project seeks to develop an autonomous water sampling payload to be mounted on an unmanned aerial vehicle (UAV). UAV assisted water sampling has numerous advantages over vessel methods for close collection. This technology has applications in mineral sampling in geological surveys, especially those with dangerous or hard-to-navigate routes (i.e. caves), as well as water quality monitoring for wildlife, pollution and climate change indicators in pit lakes and coastal areas. The utilization of UAVs for water sampling is cheaper and more accessible than traditional vessel deployment methods. It has a shorter mobilization time, allowing for more effective and frequent sampling by a minimum of one person. Many current methods of drone-assisted water sampling only intake small amounts of water at the surface level. This project intends to provide a controlled and sufficiently large sample for testing at a manageable cost to researchers, such as those at the Virginia Institute of Marine Science.

2 Background

Most current drone-based water sampling designs fall into one of two categories: a tube and pump design or an open bottle design. The tube and pump design consists of a 3d printed chassis which holds a few, typically 3, 20ml screw-top glass vials with spring-hinged lids, connected to a dangling tube that sucks up water to the assembly and into each vial [1]. The tube is directed to each vial by means of a servo motor, which operates in five positions (160 degrees), allowing for two water jettisons, one between each vial, preventing contamination between samples. This design, while temporally and spatially efficient, cannot perform deep-water samples or large samples in a timely manner sufficient for drone use. The open bottle design functions primarily as an assembled cage which houses an open-top bottle to hold the water sample [2]. While this design is simple, easy to exchange, and cost effective, it cannot control depth, provide multiple samples, or protect the sample from environmental factors in flight. Ultimately, each drone assembly currently researched has some hanging component, whether this is the actual sampling container, a suction tube, or other mechanism. This prevents effective maneuverability of the drone. In designing our attachment, we considered incorporating a winch system that allows for the samples to reside close to the center of mass of the drone.

The choice of sampling container was broken down into three options: the Niskin bottle, the Bambi bucket, and the HydroSleeve. The Niskin bottle is a capsule-like device that automatically closes based on a trigger, typically a messenger weight. It is air-tight, but most niskin bottles available for purchase were made of a material too heavy to be of use for drone-assisted sampling. The Bambi bucket is a large piece of canvas-like material that scoops up water as it folds like a draw-string pouch. This sampling container, while simple and able to acquire large quantities, is not feasible for depth samples and does not protect the sample from environmental factors during flight. The third option, the HydroSleeve, is made of collapsible polyethylene tubing with a self-sealing reed-valve. It is a hanging assembly which is lowered to the desired depth and fills from the top when the tubing is raised. This container did not prove effective for surface samples, which is one of the depths at which we desire to sample.

3 Payload Specifications and Design Process

3.1 Initial Goal Specifications

MVP

- 1 liter sample at controlled depths
- Maximum 17lb payload
- Sun-proof, air tight, no headspace
- Emergency Release System

Future

- Temperature Sensor
- Metal winch to support depth samples
- Multi-sample capability
- Capability to house other desired sensor(s)

3.2 Final Specifications

Aurelia X8 Payload

- 1 liter sample at surface
- 17lb max payload
- Sun-proof, air tight, no headspace
- Emergency Release System

Tarot 650 Payload

- 0.15 liter sample at surface
- 3lb max payload
- Sun-proof, air tight, no headspace

3.3 UAV Status

Throughout the year, we had many difficulties impacting our use of the drones, which significantly affected the specifications of our payload. Throughout the following section, there will be interjections detailing a drone event that impacted our development.

3.4 The Sampling Bottle

Drone status: We did not have access to the Aurelia X8 or the Tarot 650 throughout the entirety of the first semester. Our design philosophy was to develop a payload that would meet the weight requirement of the Aurelia X8, while focusing on the bottle itself rather than the mounting of the payload to the UAV.

We chose to design a pvc niskin bottle prototype for our water collection device. We adapted the niskin bottle designed for the Niskin3D project by OceanographyforEveryone [3]. This design is a tube with a volume we chose to be approximately 1.2 liters and a length that doesn't exceed the width of the drone body. On either end of the bottle is a rubber stopper, connected inside the tube via elastic latex tubing, and held in tension. The outside ends of these stoppers are held out of the bottle by a paracord line, which is connected to a trigger mechanism on the tube. This trigger will release the line holding the stoppers out of the tube, allowing it to snap shut via the elastic tubing inside. The extra 0.2 liters of volume inside the bottle accounts for the volume of the stoppers and elastic cord.

3.5 A Trigger Mechanism

The trigger mechanism of the payload has undergone many iterations over the course of the semester and is the primary component of the project that varies from that of the Niskin3D project. We began by deciding whether we could use a servo motor to trigger the water collection, as was designed for the Niskin3D. We ultimately found that running control wires down from the drone would be a difficult feat and there were no servos rated for the underwater time and depth we required. We then moved to mechanical triggers in order to solve the issue of running wires down from the drone. One trigger idea we explored was a spring resisted pressure surface. This would allow water to flow into the bottle when the pressure due to the water exceeded the opposing force of a spring. The spring would have a carefully chosen spring constant to control the depth at which water entered the bottle. This idea was ultimately rejected in the design phase as the flaws became apparent. This method required a different spring for every depth, did not allow the bottle to be flushed as it was descending, and was subject to accidental triggering by turbulent water on descent. These issues were overcome-able, but required a lot of complicated design. The flaw that ended this attempt was the fact that a cavity of one atm would have to be in place behind the pressure surface in order for the depth sampling to be accurate. A large cavity such as that would increase the buoyancy of our payload a significant amount. This would then require more weight to drag to depth, which meant more weight that the drone would have to carry, resulting in a significant loss of flight time.

The next trigger idea looked much more promising than the pressure trigger. We experimented with using a nichrome burn wire to burn the line holding the stoppers out of the tube. Nichrome is a highly resistive wire that heats rapidly as current is run through it. This was tested in both air and water, and the power and time required to burn the line was measured. This mechanism solved many of the problems presented by the earlier two ideas except for needing to run wires down to the payload, however, we decided to face this challenge when it arose. Both fortunately and unfortunately, we never reached that point. The burn wire worked perfectly in air, however, when tested in a saltwater solution with a salinity roughly equal to that of the ocean, the wire shorted and did not heat up. In order for the wire to burn the line, it would have to be within a cavity, which would cause a buoyancy issue similar to the last trigger method. This burn wire trigger mechanism was then scrapped in favor of a new trigger for which new issues arose.

The new trigger mechanism idea was a linear solenoid attached to a pressure sensor via an arduino microcontroller and relay. This would be a battery operated circuit encased in epoxy to protect it from the water, except for the waterproof solenoid that will act as a pin being pulled to release the line and shut the niskin bottle. We spent around half of the semester working with the solenoid and testing its capabilities. We were able to get code working for the pressure sensor relay connection. This operated very well and could still be applied to our current design with a little modification.

Drone Status: It was at this point in the design process that we obtained the UAVs for use and began planning to test our prototype bottle and trigger mechanism.

Through testing the solenoid, we ultimately discovered that the lines attached to the stopper were supplying a transverse load to the solenoid pin. This caused increased friction with the edge of the solenoid body and dramatically reduced the strength of the solenoid to the point where it could not trigger the bottle. We then redesigned the trigger system in order to work with a snap shackle. This shackle takes the transverse force which allows the solenoid to pull with its full force. We found out after running tests with the shackle that linear solenoids have a very strong resistance to force once triggered, however, they are not very strong when pulling. We modeled a case for the relay and battery to be attached to the underside of the drone for the Tarot 650 and to the niskin bottle for the Aurelia X8. This design secured the individual components. Ultimately, we decided that the linear solenoid was not strong enough to trigger the bottle and we could not increase the power of the solenoid without increasing the weight.

Drone Status: At this point in the process, the Aurelia X8 suffered a fatal crash that rendered the UAV grounded for a couple of weeks. We then decided to shift our focus to a scaled down prototype bottle that would meet the weight requirement of the smaller drone, the Tarot 650. This smaller prototype was designed with the intention of proving the viability of our design, and then scaling up to the Aurelia X8 when repaired.

In the interest of time and in order to meet the weight requirement of the smaller drone, we decided to revisit the servo trigger discussed earlier. Testing the servo in water proved that we could take a surface sample without damaging the servo motor. We then decided to continue with the servo trigger and work with running cables down to the payload. The servo-powered trigger is shown in figure 1, with the pin and and joint components printed with carbon fiber inlay. During priming of the bottle, we discovered weakness in the u-bend of the model, which caused a tear resulting from the tension of the stoppers. Thickening this area proved sufficient for later test samples.

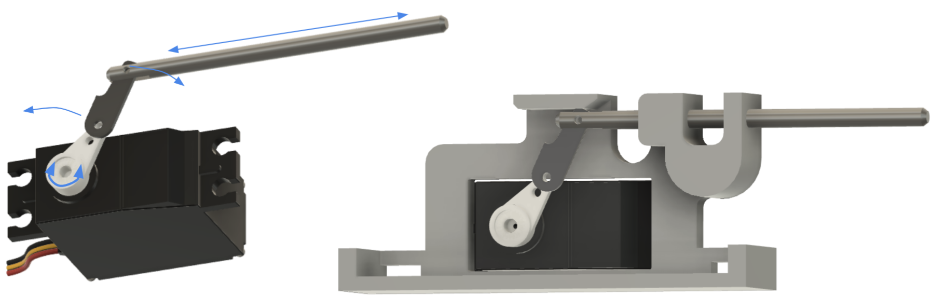

Figure 1: The design of the servo trigger mechanism.

3.6 Final Tarot 650 Bottle Design

Due to complications with the Aurelia X8 as mentioned, the first prototype bottle we built was the small bottle which fit on the Tarot 650. This bottle held approximately 0.15 liters of water. This is not enough water to perform testing on, however, this prototype was only built as a proof of concept before scaling up to the 1-liter bottle to be mounted on the Aurelia X8. A labeled Fusion 360 model of the small bottle is shown in figure 2. The rubber stoppers on either end are connected to each other on the inside via elastic tubing, while the I-hooks on the outside of the stoppers are connected via paracord to the servo pin, which releases the cord and seals the bottle.

3.7 Bottle Mounting Design

In order to mount the bottle to the UAV, we had to consider many factors, including the prop wash of the UAV, the hanging point of the payload, the wire connections from the bottle to the UAV, and many more. To tackle these obstacles, we performed many test flights of the UAV under weight to observe the effect of flight on the payload and UAV. These tests were performed at Martin Family Stadium, a W and M lacrosse field. Our weighted first flight test involved 3 lines attaching the payload to the UAV, where the payload was a weight with around the same anticipated weight of our final bottle, with a similar aerodynamic profile. We had one line attached to the center of mass on the underside of the UAV, and two more non weight bearing lines attached to either UAV leg in an attempt to mitigate in-flight twisting. We still observed twisting, which was likely exacerbated by the extra lines, however, we did not observe any dangerous positive loop pendulum motion that could have taken down to UAV. We performed various more tests at different hanging lengths,

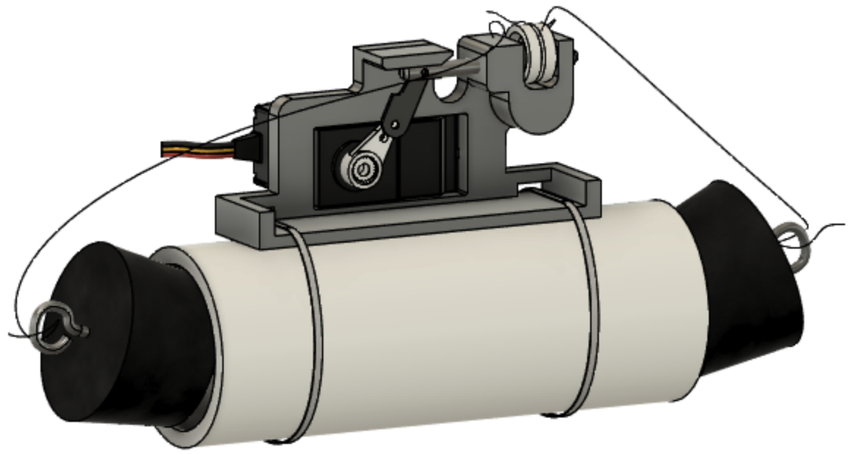

Figure 2: The Tarot 650 Bottle Design in Fusion 360.

ultimately deciding that one line was ideal. We attempted to mitigate twisting in other ways as well, such as fins and flags attached to the payload. We observed little mitigation and decided that since our payload is not directionally confined, the small level of twisting we saw was acceptable.

The next challenge we faced in mounting the payload was the wires we were required to run down to the servo. We used a ribbon cable, which was connected to the servo wires via solder and a water resistant heat shrink seal. The ribbon cable was then fed into a power reducer board, pulling power from the UAV batteries, and then fed into the Pixhawk flight controller's GPIO output, so that we could remotely control the payload trigger from the controller. The release signals and controller bindings were set up with Professor Frey's help in two applications called MissionPlanner and OpenTX. A successful test of the small bottle is given at this link: Tarot 650 Bottle Test.

3.8 Final Aurelia X8 Payload Design

After a semi-successful wet test of the small prototype on the Tarot 650 at lake Matoaka, the Aurelia X8 was in a place where we could begin to scale up our design. We built the large bottle to hold 1.2 liters of water. 1 liter was the minimum and the 0.2 extra was to account for the stoppers and elastic tubing that reside within the bottle. In order to avoid an extremely long bottle, we elected to use a 3 inch ID PVC pipe. The weight of stoppers increases very quickly so we used PVC pipe reducers so that we had a smaller opening to plug, allowing us to use smaller stoppers. We ran into problems securing the I-screws into the stoppers as the tension from the elastic tubing was more than the rubber cement could handle. Will Henninger helped us solve this problem in the machine shop by using one rod of metal through the center of the stopper and curling it into a loop at both ends. This allowed for attachment at both ends through the loop and prevented any part from slipping out of the stopper. Finally, we redesigned the bracket holding the servo trigger assembly to prevent it from detaching from the bottle like the Tarot 650 prototype did.

We could not hang this bottle from the ribbon cable as we were able to for the small bottle due to the significantly increased weight. We also had to implement an emergency release mechanism to drop the payload if necessary. Given these two factors, we had to redesign how we hung our payload. We decided to hang the payload via paracord instead of the ribbon cable in order to hold the weight. We also added a parachute swivel to mitigate some twisting of the bottle during flight. This paracord ran up to a servo motor mounted on the underside of the drone. This servo acted as the emergency release that would drop the payload when triggered. To negotiate the wires that needed to attach to the payload, we fed these into a connector on the power reducing board that was oriented vertically so that the connection would disconnect when the weight of the bottle was applied to it, i.e. after dropping the payload. This emergency release mechanism is shown in figure 3. Finally, we noticed issues in earlier tests where the drone was influenced by the attached payload on takeoff and landing. This was solved by adding a loop to the payload and a carabiner to the paracord line so that the payload could be attached or detached after takeoff or before landing respectively. The final Aurelia X8 bottle is shown in fusion in figure 4. The primed bottle is shown in figure 5.

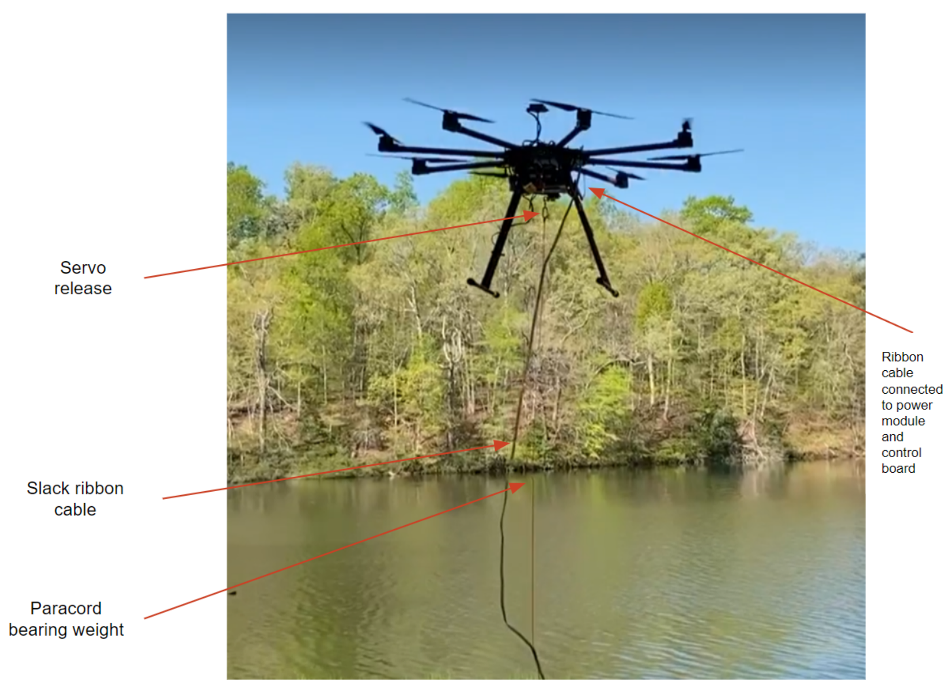

Figure 3: The labeled emergency release system in flight.

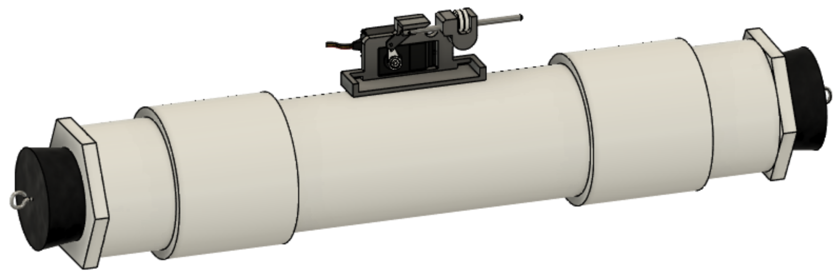

Figure 4: The Aurelia X8 Bottle Design in Fusion360.

4 Final Successful Water Sampling Payload Test

We were able to successfully retrieve a sample of water from lake Matoaka of at least 1 liter that met our minimum viable parameters. This flight was performed manually due to concern about the Aurelia X8, however, it is fully capable of taking an autonomous water sample. A video of the successful sampling, with a payload camera overlay, is given at this link: Final Successful Water Sampling Payload Test.

5 Challenges

The biggest challenge we faced in this project was the inability to work with the drone we would be using. This is because in the first semester, there were issues in the shipping of the drone independent of our work. At the beginning of the second semester was the initial crash of the Aurelia X8, which occured on our first test flight. The LIDAR package was faulty, we discovered, and as a result, caused complications and disagreement between the GPS coordinates read from the satellites and the magnetometer's readings. Over the next month, the drone was rebuilt, though we continued to have issues with its flight performance. The magnetometer was mounted to a tower and off-centered in an attempt to prevent magnetic interference from the electrical components of the drone board. Eventually, the LIDAR system was stripped from the drone and we proceeded to test the payload design manually. As a result of this experience, we decided to downscale our design to fit the small fleet of drones - the Tarot 650 - and would be built up to the large drone once it was fixed. This also made us realize the need for an emergency release of the payload, in the case that it became entangled or caught on something, such that it would not take the drone down with it. We designed a connection method and trigger to release the paracord bearing the weight of the payload and connected the wires such that they could easily snap on or off.

A second challenge we faced was the weight consideration of the project. The drone has a flight time that decreases as more weight is added to the payload. For this reason, we had to minimize weight in as many areas as possible. This includes choosing materials for various

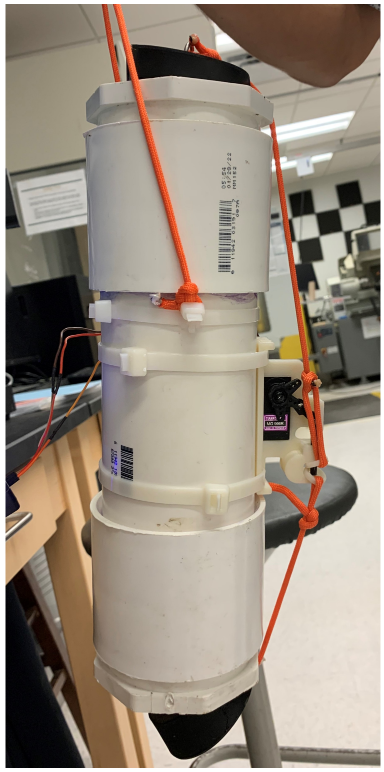

Figure 5: The Aurelia X8 Bottle in its primed state.

parts of the payload that meet the necessary specifications while also serving as lightweight.

A third challenge we faced was the trigger mechanism for the closing of the niskin bottle. The initial testing of the burn wire failed due to the interaction with salt water and nichrome shorting out the wire, and we were left to determine a suitable replacement that could withstand being submerged in the water while not over-complicating the entirety of the system's design. We researched an Arduino-controlled trigger with a linear solenoid, activated by a pressure sensor. We used the time over winter break to familiarize ourselves with this design and learn the coding necessary to control this. Upon testing this design more, we ended up moving back to the servo motor. The trigger mechanism went through many iterations but we ultimately landed on a trigger viable for surface sampling that met our minimum requirements.

6 Potential Future Improvements

6.1 Preserving Sample Quality

In order for our payload to be used by researchers to collect a water sample for testing, some materials need to be changed. The PVC pipe is one that should be switched to polycarbonate tubing because PVC can leech plastics into the sample while polycarbonate keeps the sample pure. The elastic tubing also must be either changed or treated for the same reason.

6.2 The Winch

The raising and lowering of the payload was to be accomplished via a winch system mounted to the drone. A system in which the payload is raised and lowered was deemed favorable for drone maneuverability as during flight, the center of mass is much closer to the drone when the payload is raised. The winch system functions via a dc motor connected to a motorized deep sea fishing reel. As a result of the in-accessibility of the larger drone, and consequent focus on designing for the smaller drone, we eliminated the winch system from our minimum viable product, which would have been too heavy to be supported by the smaller drone as it was. While we were unable to develop this further, we finish with the notion that the best way to connect the winch to the drone, assuming the use of the motorized fishing reel, would be to secure the foot of the reel to a series of four light-weight metal plates, which can be secured to the underside of the battery bay of the drone by nut and bolt. Other designs might make use of the four pillars at each corner of the bay. This is an addition we hope to be added in the future to accomplish a depth sample.

6.3 Linear Solenoid Actuated Trigger

We researched and tested the use of a linear solenoid actuated trigger, but ultimately had to move to the servo trigger considering the drone situation and in the interest of time. We do still believe that a linear solenoid is the best route for the trigger as it can act fully independently of the drone, no wires need to be put in place, and it is incredibly water resistant. We hope a future group will be able to solve the problems with the linear solenoid trigger that we did not have time to.

6.4 Capability to Attach Desired Sensors

Finally, a large improvement on the payload would be the ability to attach a researcher's desired sensors. The ability to sense various qualities of the water that you are sampling, such as temperature, pressure, salinity, etc. would have a profound impact on the quality of data received from tests of the water sample.

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