Aerial Ecological Monitoring Using a Low Cost DIY fixed-wing UAV

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Ecosystem monitoring using imagery is often accomplished with off the shelf quadcopter UAVs, such as the DJI Phantom 4 Pro, which offers a cheap, easy to use method for capturing imagery for land cover classification. However, these drones are not well suited for large scale ecosystem surveys, as they are not robust enough for harsh weather conditions and have limited flight times. An alternative solution which offers more robust airframes and higher survey efficiency are fixed-wing UAVs, but current off the shelf fixed-wing solutions have high costs, deeming them unattainable for many surveyors. This project proposes a fixed-wing DIY aircraft with custom components that can address the issues mentioned above at an acceptable budget. Our custom aircraft will have a Raspberry Pi Camera and NoIR camera for RGB and Near-Infrared image capture, respectively, with a Raspberry Pi to manage the dual sensor payload. The airframe will include a flight controller integrated with radio telemetry and GPS components to control the aircraft and potentially perform autonomous flight for survey imaging. With a final price of under 700 dollars and ultimately being able to achieve a final image resolution of less than 10 cm/pixel through survey tests, we hope that this DIY fixed-wing UAV will provide a low cost alternative to quadcopters and other high cost fixed-wing aircraft.

Additional Key Words and Phrases: UAV, drone, fixed-wing, remote sensing, ecosystem monitoring

1 INTRODUCTION

Ecological monitoring is a field in remote sensing that is vital to tracking changes in important ecosystems all across the world. With global warming accelerating and many countries creating goals for environmental conservation, the ability to track these ecosystems are becoming more and more important. Ecosystem monitoring is typically done through multiple sources, mainly through satellites and aerial surveys. Satellites are easily available, but oftentimes satellite imagery cannot give high enough resolution to give the fine-grained detail needed to track small changes in ecosystems. Therefore, high resolution aerial imagery is used to capture such small changes. The most commonly chosen method to capture aerial imagery is through UAVs.

1.1 Quadcopters

Our group has used off the shelf quadcopters, specifically the DJI Phantom 4 Pro (P4P), to capture imagery and track changes in mangrove ecosystems. These UAVs have many advantages, mainly related to their ease of use and imaging quality. The P4P can be easily flown by anyone with little training, as it has automated flight and automated or easy takeoff and landing. In addition, these UAVs can capture reliably high resolution imagery as the P4P's camera is mounted on a gimbal, and has a mechanical shutter, which reduce motion blur and other image aberrations when the UAV moves at a fast speed.

However, quadcopters such as the P4P can struggle when applied to large survey areas for several reasons. First, although the P4P can capture high quality imagery, it captures these images at a slow speed, with a maximum airspeed of 15 m/s. In addition, quadcopters are much more limited by battery life, as their batteries are oftentimes non-upgradable and have battery lives of less than 30 minutes. Thus, low airspeed compounded with lower battery life can result in longer surveys, as significant time must be taken to change out batteries or even switch landing and takeoff positions due to lower range. Also, quadcopters like the P4P are heavily affected by the wind, leading to further issues. When quadcopters like the P4P face a headwind, their survey speed can be impacted greatly, sometimes bringing quadcopters to a standstill in high winds, slowing down the quadcopter's forward velocity, and therefore slowing their survey speed. Furthermore, when quadcopters encounter a crosswind, they can be shifted off course through rotations of the quadcopter and add significant motion blur to images. Lastly, one of the most negative effects that winds can bring to these quadcopters is increased strain on the aircraft due

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to winds. Since the force of the motors is exerted on the motor arms of the airframe, when strong winds are experienced, the additional force of the winds, and subsequently the additional force of the motors to counteract that wind, is also exerted onto the motor arms. These additional forces can lead to stress fractures in motor arms, rendering a quadcopter unsafe to fly, completely halting surveys. These issues are compounded when doing large surveys, as these forces are applied over many flights, and can further increase the chance of airframe failures. Issues around airframe durability also would not be as severe if the these aircraft were more repairable, but P4P's use proprietary parts, making field repairs near impossible.

1.2 Jamaica Survey

Our group faced these exact challenges during a recent research expedition in Jamaica, where we focused on the monitoring of mangrove ecosystems. Due to the fact that mangroves are coastal, we faced strong coastal winds on a daily basis. Also, this survey area was considerably larger than our past surveys, as we were tasked to survey over 50 km^2. Due to these winds and large survey area, both of our P4P quadcopters received stress fractures as seen in Figure 1, and were deemed unusable. We then attempted a repair of these two quadcopters as also seen in Figure 1, but in order to do this, one of the aircraft had to be cannibalized, limiting the team to only one P4P. Thus, our already slow survey speed was halved, and ultimately our group was unable to capture imagery of our entire survey area. We then relied on satellite data to survey our area, which then deemed most of the data captured with the P4P useless. If an alternative monitoring platform was used, the failures experienced during this survey could have been easily avoided.

Fig. 1. Pictured Left and Center: Airframe stress fractures on P4P UAV, Right: P4P Repair Process

1.3 Fixed-wing UAVs

As an alternative to quadcopters like the P4P, surveyors oftentimes use fixed-wing UAVs. One main advantage of fixed-wings over UAVs is their survey speed. Fixed-wing planes can fly much faster than quadcopters, oftentimes having a minimum airspeed of 15 m/s which can be the maximum airspeed of many quadcopters. Another advantage of fixed-wings over quadcopters is their payload capacity. A large payload capacity enables longer surveys, as much larger batteries can be used compared to quadcopters, enabling fixed-wing UAVs to have flight times of over an hour. In addition, this increased payload capacity allows for much more flexibility in camera payloads. Our P4Ps' cameras cannot be upgraded or changed, but a fixed-wing plane with considerable payload capacity can utilize small action cameras such as GoPros, larger full cameras such as mirrorless cameras, and even custom DIY camera sensors.

These advantages are mainly because of aerodynamic properties of fixed-wing aircraft, which enables fixed-wing aircraft to be more durable over large surveys than quadcopters. The materials of fixed-wings are not stronger than quadcopters, as they are oftentimes composed of foam, instead of the carbon fiber or plastics that quadcopters are composed of. However, due to fixed-wing UAVs being able to counteract forces with flaps rather than directly on the motor arms, strong forces due to winds can be spread out over the wings and flaps, reducing the chance of airframe failure. Thus, these fixed-wing planes are are more durable when used for large surveys and in areas of high winds and adverse weather conditions.

However, fixed-wing UAVs are not a perfect alternative to quadcopters as they do have some disadvantages. One main disadvantage is their ease of use, as fixed-wing planes are significantly harder to fly than quadcopters as both takeoff and landing require significant practice and training. In addition, when using fixed-wing UAVs, surveyors have less versatility when choosing a take off and landing area, as one needs a significantly larger horizontal area when compared to quadcopters due to fixed-wings needing to land horizontally, rather than the vertical take off and landing of a quadcopter. Lastly, the most significant disadvantage of fixed-wing UAVs is their cost. Off the shelf fixed-wing aircraft such as the Wingtra One and eBee X can oftentimes cost over $20,000, not including the camera, which is a significant upfront cost compared to other quadcopter options.

1.4 Thesis

Therefore, we propose a low cost, fixed-wing UAV aircraft that has similar capabilities to vastly more expensive fixed-wing aircraft, while being a fraction of the cost. This fixed-wing should also inherently improve on many disadvantages of quadcopters, enjoying faster survey speed and longer surveys, while still being able to capture quality, high resolution imagery. Furthermore, this UAV aircraft should be built from off the shelf parts and an off the shelf airframe. This plane should also be able to fly autonomously via a ground station connected via telemetry to fly autonomously. Lastly, this proposed aircraft should also be able to capture quality images, with a goal resolution of less than $6pix/cm^2$ and a final digital elevation model (DEM) resolution of less than $12pix/cm^2$.

In summary our contributions will include:

- A low cost DIY fixed-wing UAV
- Faster survey speeds and longer surveys than off the shelf quadcopters
- Comparable imagery to other UAV platforms

2 RELATED WORK

Aerial photography has long been considered as an important way of monitoring the mangrove forests and other plantations, but for a long time, researchers have been mostly focused on satellite imagery because the high cost of survey using manned aircraft and drones [2, 4, 5, 8]. But in the past decade, the ability of consumer drone systems have experienced a great leap, while the prices have became more and more affordable. Along with other open sourced platforms, drone surveying has become increasingly promising [3, 7]. In past research, drone imagery has shown an significant performance lead even over the newest high-resolution satellite imagery like Pleiades-1B, which has a resolution of 50 cm/pixel [9]. However, the drones used for surveys today still have some limitations. In particular, these surveys mostly use quadcopters which are relatively slow in terms of survey speed, so the survey speed is limited when compared to satellite imagery [6]. So, some researchers have proposed fixed-wing UAVs as an alternative to the quad copters [1, 10]. According to this research, fixed-wing UAVs have comparable imaging resolution with quadcopters while having a much faster survey speed. One problem of the previous works on fixed-wing UAVs is that most of them uses a high-cost camera systems like DSLR cameras, which greatly increase the cost and complexity of such systems [10]. Thus, our fixed-wing aims to improve on the disadvantages of the past researches of drone systems and aims to reduce complexity which can lead to a lower cost.

3 METHODS

3.1 System Design

As an overview of the system design, the aircraft consists of these primary components or sub systems: a Pixhawk flight controller, telemetry, sensors and a camera module. The Pixhawk flight controller is the central control unit of the aircraft. It is responsible for connecting and controlling the servos and motors, as well as all the sensors, telemetry system, and receiver. The Pixhawk allows us to control the components of the aircraft and process commands sent from a ground station or remote control, and gather data from sensors such as GPS location and airspeed to feed back to the ground station. Telemetry enables us to have this functionality, where one end is connected to the Mission Planner PC ground station and other end connected to Pixhawk. The Pixhawk also need other information as mentioned in the first paragraph in order to help the autopilot control in Mission Planner, thus we have a GPS module and an air speed sensor. The GPS module can also help record geographical locations of the images that are recorded in the camera module. Finally, our experimental camera module can be combined into the fuselage of the aircraft. The module consists of a Raspberry Pi, a IMX219 camera module and a 3D printed frame to hold both of these. The Raspberry Pi contains a script that automatically runs at startup to record images at a given interval, which will satisfy our requirement for autonomous surveying. For our main imaging sensor, we utilized a GoPro Hero 10 installed in the same location. A simplified system diagram that describes the above platform is shown in Figure 2. Table 1 is also a simplified bill of materials for our final fixed-wing UAV.

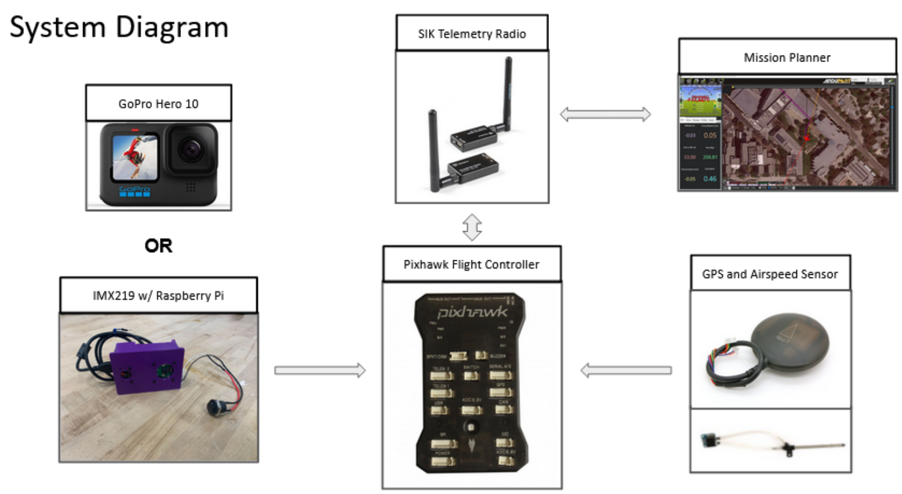

Fig. 2. Simplified system diagram of our fixed-wing UAV

3.2 Airframe Building

To support the required sensors and auto piloting systems, we needed an airframe that has enough internal space and at the same time, needs to be easy to be disassembled for transport to the survey site and assembled on site. To achieve such abilities, we decided to choose an air frame kit from the market, a ZOHD Skyhunter 1800, and assembled it on our own. We chose this airframe as it has a large payload capacity, allowing us to have flexibility in camera selection and internal batteries. Our final survey platform is pictured below in Figure 3.

Parts	Price ($)
ZOHD Skyhunter 1800	209
Admiral LiPo Battery	66.99
Ublox Neo M8N GPS Module	22
Airspeed Sensor	46
SiK Telemetry Radio V3	68.95
PIXHAWK Flight Controller	179
FrSky Taranis X9D Transmitter	100
FrSky G-RX8 Receiver	49.99
Raspberry Pi 3b	60
ArduCam IMX219 Camera	29.99

Table 1. Bill of Materials of our fixed-wing UAV and custom camera system

Fig. 3. Our built survey platform based on the Skyhunter 1800 fixed-wing airframe

One problem we encountered when integrating the systems together was that there is no place to mount the survey camera outside of the aircraft safely. We decided to cut a hole in the bottom of the fuselage and designed a custom mounting frame to put on. This custom mounting hardware also provides us the ability to quickly swap the camera payload and provides possibility to fit on other camera modules to the our UAV. As long as the weight permits, We can design an adapter for any camera system we want to use and easily swap them in if desired as shown in Figure 4 .

3.3 Sensor Payloads

As mentioned before, the experimental camera sensor consists of Raspberry Pi and IMX219 Camera. We implemented this custom sensor due to the high cost of other cameras commonly used in similar platforms. In addition, such a custom camera platform can enable multi-spectral imagery at a fraction of the cost of sensors such as the Parrot Sequoia. Our custom sensor does not currently have multi-spectral capability, but this is a feature we would like to implement in the future. A simplified system design of this proposed camera sensor is shown in

Fig. 4. Pictured Left: GoPro mounted in nose of fixed-wing, Right: Mounting hole for sensors

Figure 5. For our main imaging sensor, we also used the GoPro Hero 10 for our trial as this was what was first proposed as our imaging solution, but without software control. Below in Table 2 is a comparison of different camera sensors, and below in Figure 6 is a graph showing the spatial resolution of these sensors at different resolutions.

Cameras	**FOV (degrees)**	**Resolution**	**Cost ($)**
Go Pro Hero 10	93.3 * 70.4	5568 * 4176	400
Sony A6400 w/16mm lens	69.1 * 49.3	6000 * 4000	1500
DJI Phantom 4 Pro	84.0 * 61.9	4000 * 3000	N/A (Full system 1500)
Parrot Sequoia	63.9 * 50.1	4608 * 3456	3500
Our custom camera system	62.2 * 48.8	3264 * 2448	~100

Table 2. Comparison of different camera sensors

3.4 Custom Camera Software Design

Our custom camera module utilizes a Python script that runs on the Raspberry Pi platform. This script automatically starts at the startup of the Raspberry Pi and starts recording images at a given interval, ensuring that these images can be processed later into usable survey imagery. We set the camera to start record based on the altitude of the aircraft so we can avoid recording unnecessary images during takeoff or landing. We also created a Python module for organizing all the recorded images in a consistent order. Every time we start a new flight, the python script will create a new flight folder and put the recorded images into the new folder. We name the images as "date+latitude+longitude+altitude". In this way, we can use this location information for georeferencing.

To explain how images are captured, we setup the connection between the Raspberry Pi and the Pixhawk by calling a connect function from Dronekit library, then we setup the camera frame for capturing images and get the date time information. After that, we use a function to check the existing flight folders and make a new flight folder. We then use a while loop to continuously capture frames from the camera. There is a if statement which is used for check whether the current altitude is good for recording or not. Also, we put a line the end of if statement to ensure that there is a time interval between taking pictures. This is workflow is described in Algorithm 1.

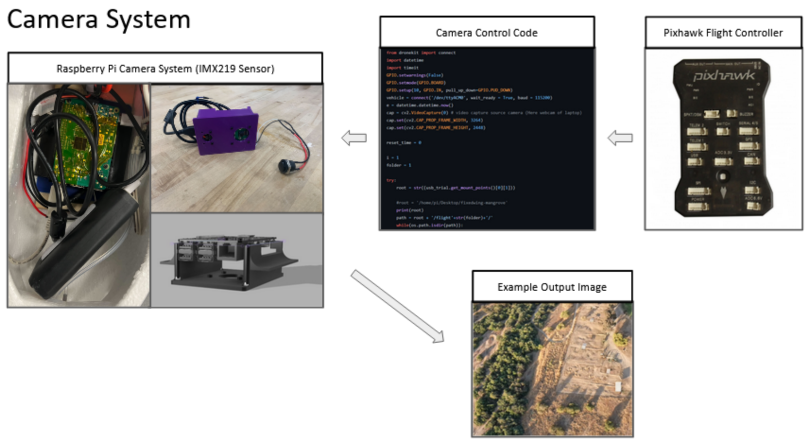

Fig. 5. Simplified system diagram of our camera system included images of mounted camera sensor and 3D models.

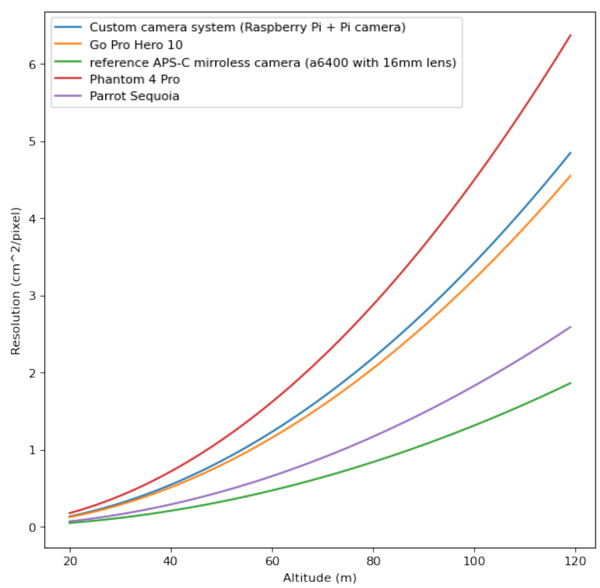

Fig. 6. Plot of spatial resolution for various cameras at different altitudes

4 RESULTS

4.1 Test Flight

In order to test our fixed-wing we planned a test flight to test the systems that we engineered. We faced some logistics issues, as we had to cancel our first test flight due to our original pilot being unavailable, so we planned another test flight with a different pilot a week later. In summary, we planned 3 flights:

Algorithm 1 Camera Control Algorithm

```
Start Camera
Connect to UAV via MAVLINK
Get USB driver address
while True do
    Capture frame
    if Altitude > 50 then
        picture ← camera
        usbaddress ← picture ▹ The image is named following the format "date+latitude+longitude+altitude"
        Wait for 1 second
    end if
end while
```

- **Manual Flights**: These flights are to adjust the aircraft's center of gravity (CG) and see if there are any issues with the airframe. For all of these manual flights, we had our GoPro installed in the aircraft to record imagery without the need for autopilot to work, and so our CG was consistent.
- **Tuning Flights in Autotune**: This is to tune the aircraft so stabilization modes will work and so autonomous flights can be flown
- **Autonomous Survey Flights:** These flights are to test our custom imaging sensor and our GoPro for direct comparison.

Our first flights went very well, with no issues related to the flight of the aircraft once the CG was adjusted. Other than adjusting the CG and a recalibration of the accelerometer and compass, no other adjustments were needed to be made to the aircraft. From these flights, we recorded video and imagery from the GoPro mounted within the aircraft. We also tested the battery draw from these flights to get an approximation of flight time, which we estimated that with two batteries installed, we could get an approximate 50 minute flight time.

Next, we attempted to PID tune the flight controller using the Autotune mode. Our flights started as normal, but we found that when in autotune mode, the fixed-wing was unresponsive to pitch control, and had a tendency to pitch downwards. We noticed that we were getting some errors with the airspeed sensor, so we then spent the remainder of our test flight attempting to fix the issues related to the airspeed sensor, but to no avail. Because of this, we were unable to tune our aircraft during our second set of flights and subsequently, we were unable to test autonomous flight or our custom imaging sensor during these flights.

4.2 Image processing

Even though we weren't able to accomplish an autonomous flight with our fixed-wing, we still ensured that imagery was recorded during all of our manual flights from our GoPro, and thus we could process these images with Agisoft Metashape. Below in Figure 7 is an example final processed orthomosaic and DEM from one of our flights with only 72 images.

The final processed imagery is impressive to say the least, and has good details across the entire image. The edges of our images do have some stretching due to the wide angle lens of the GoPro, but these stretched areas can simply be clipped from the final image. Our DEMs also seem fairly accurate, and have little elevation errors, which can partly be attributed to the wide angle lens as well. Our final results had a $2pix/cm^2$ and a $11pix/cm^2$ imagery and DEM resolution respectively, well within our objectives for our image quality.

These final images were around $1/8km^2$ in area, with the flight that took the original imagery lasting approximately 1-2 minute flight. Thus, our fixed-wing has an approximate survey speed of around $5km^2/hr$, a speed that is much faster than the P4P. From these estimates, if our team had this fixed-wing in Jamaica, we could have

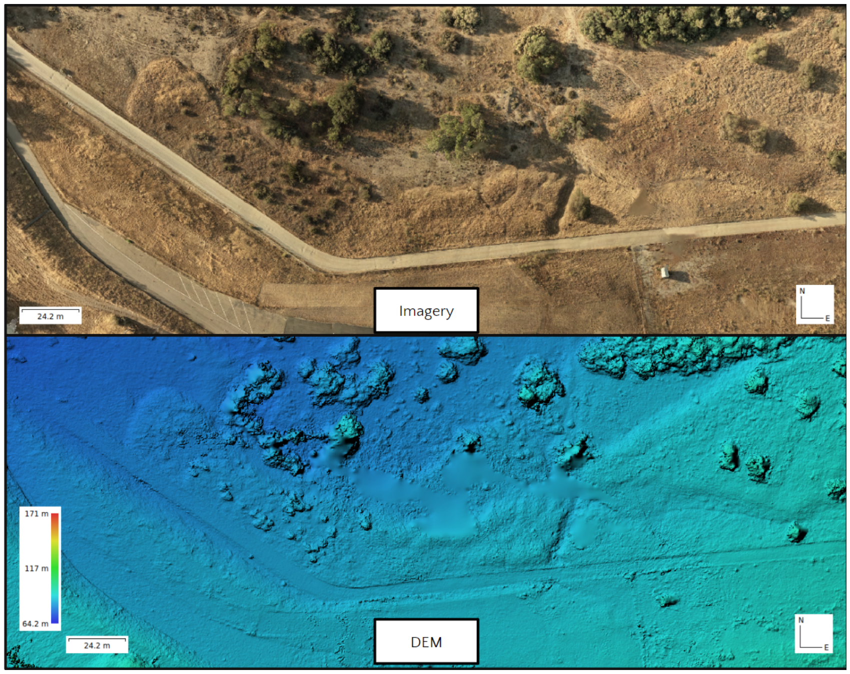

Fig. 7. Pictured: Orthomosaic and DEM Recorded from GoPro camera

surveyed the entire survey area in Jamaica within a few days, instead of only being able to capture half of the imagery over a few weeks.

4.3 Final Comparison

To summarize, after the test flights, we found that our DIY fixed-wing aircraft has higher performance than the P4P in both survey speed and flight time while still cost a fraction of other fixed-wing options. In other words, our DIY fixed-wing aircraft shows a great potential in surveying ecosystems. We have included below in Table 3 a quick comparison between our fixed-wing aircraft and other off the shelf options mentioned.

Aircraft	**Flight Time**	**Fully Configured Price**	**Survey Speed**
Our fixed-wing	50min	$700	$5km^2/hr$
DJI Phantom 4 Pro	20min	$1600	$0.625km^2/hr$
Wingtra One	60min	$23000	$6km^2/hr$

Table 3. Comparison between existing survey UAV platforms

5 MILESTONES

For our project, we have our milestones segmented into four subsections: **procurement, airframe integration, software design, and Mechanical Design.**

5.1 Procurement

- **BOM**: We finalized our BOM as scheduled but the time we spent on waiting for parts to arrive took longer than we expected plus we had to wait a considerable amount of time for this BOM to be approved. As a result, our other milestones also got pushed forward.

5.2 Airframe Integration

- **Airframe Building** We finished our airframe building directly after we received the airframe, but this was done behind the schedule because of the delay in arrival.
- **Install flight controller and verify telemetry and controls operations:** We also encountered issues related to driver support between mission planner and telemetry, and had to completely reconfigure the telemetry to get stable connection between ground computer and aircraft. This was done in the alloted time but behind schedule

Our original plan to use GoPro Hero 10 as the main camera with an ESP32 boards to control it through Wifi was cancelled due to incompatibilities between the GoPro Hero 10 and the API that controls functionality of the camera. This required a large change in both software and mechanical design of the mounting system. As a result, we transitioned to implement a custom sensor which used a Raspberry Pi and IMX219 Camera as the main module for our own DIY control camera system. Before the test flight, we successfully made our DIY Raspberry Pi camera system to work and integrate camera control with Pixhawk locally but we didn't have time to test it with any flights.

5.3 Software Design

- **Design software for controlling camera:** This was accomplished slightly off schedule due to trying to implement a dual camera system for multispectral imagery.
- **Integrate Camera control with Pixhawk:** Since the Raspberry Pi can be directly controlled by the Pixhawk, we can wire the two up directly using MAVLINK. This was accomplished on schedule.

5.4 Mechanical Design

Due to the change to our original camera system plan, we designed the new mounts for the Raspberry Pi and Pi cameras. Also, to support the air frame around the camera hole in the bottom of our fuselage, we designed a housing around that hole to ensure that our plan maintains structural integrity. In order to power additional components like servos and the Raspberry Pi which required a consistent 5V power, we used a buck converter and created a board that we can directly use.

- **Design mount for Raspberry Pi and Pi Cameras:** We designed mounting hardware for our camera setup and our Raspberry pi on time.
- **Create Power Module for Auxiliary Components:** This was completed on time
- **Design housing for camera hole:** This was completed on time.

To summarize our milestones, we accomplished all goals related to the building and integration of the aircraft. However, in terms of our project objectives, we were unable to achieve all of them due to reasons listed in previous sections. We have our project objectives listed below and whether they were accomplished.

Operational, flying fixed wing airframe

- Autonomous flying - X
- Camera mounting hardware - ✓
- Transmit telemetry (flight health) to base station - ✓
- 30m+ Potential flight time - ✓

Operational, flying fixed wing airframe

- Record GPS data of images - ✓
- Final output imagery resolution of < $10cm^2$ - ✓
- Final digital elevation model (DEM) resolution of < $40cm^2$ ✓

6 DISCUSSION AND NEXT STEPS

Although we were fairly successful in testing our aircraft and a possible imaging system, our plane does not include every feature that we had in our objectives. Since we could not test an automatic flight, this was our only objective that we need to enable in future test flights once our airspeed sensor is functional. Once we can enable this, we can realistically use our fixed-wing UAV as a survey platform. However, our fixed-wing still has disadvantages in that it is not nearly as straightforward to use as a quadcopter like the P4P. We can do many things to improve this in the future, such as configuring an auto land procedure that uses a stall float to decrease the amount of area used to land and decrease operator error. We would also like to add landing gear to decrease the wear on the bottom of the aircraft and make it easier to land. We can also make upgrades to much of the parts used in the airframe such as the telemetry radio receiver to increase range, as most of the parts in our fixed-wing are leftover parts cannibalized from older UAVs. We can also add first person view (FPV) capabilities to make the fixed-wing easier to fly when out of visual range and to allow the pilot to have better situational awareness. We can also make significant changes to the aircraft to make it easier to use in a survey scenario, such as configuring our fixed-wing as a quadplane, allowing it to enjoy both the benefits of a fixed-wing along with VTOL capabilities of a quadcopter.

To further increase the amount of available pilots, we can enable a buddy box system with our radio transmitters such that two people can fly the plane and learn basics such landing and takeoff. In summary, there are a lot of steps that we can take to make this a truly superior survey platform to a P4P, and even a comparable solution to vastly more expensive fixed-wings such as the Wingtra One.

Also, in terms of tests, we would like to experiment a lot more with our custom camera payload. Since we could not test our camera custom system in flight due to other issues related to our airspeed sensor, we would like to see how a custom camera can perform compared to off the shelf cameras, considering the high cost and low spectrum count of these cameras. Our GoPro preformed well despite the fact that it had no gimbal and a rolling shutter, and we expect the same from our custom sensor. Lastly, we can also switch out the payload to something more high quality such as a mirrorless camera, notably a camera like the Sony a6400, as the plane can easily handle this heavy payload.

As a final note, we would like to mention that building and configuring a fixed-wing UAV is a hard challenge for those who are unfamiliar with the process. Although there are a lot of resources online, it is very easy to miss basics of topics when the information is overwhelming, and our team consisted of almost complete novices to UAV building, some without any knowledge of remote sensing. A lot of lessons were learned throughout this process, but our team still successfully built our plane after many long and late hours in the lab. From this, we have set up the structure and knowledge for future improvements. **From these learnings, we have seen a large potential in the use of fixed-wing aircraft as the huge improvements in survey speed and potential survey time are hard to ignore, even if our current solution is not ideal.**

7 CONCLUSION

In conclusion, we built a DIY fixed-wing UAV for ecosystem monitoring that is low cost and can capture imagery of areas with comparable quality to other aircraft. This fixed-wing UAV used the Skyhunter 1800 as the airframe, includes other off the shelf parts which are easily replaceable and upgradable. We were able to meet many of the requirements that we set out with the project, with the plane meeting all objectives except for autonomous flight.

The imagery from our main sensor, a GoPro Hero 10, was also comparable to other UAV solutions creating final orthomosaic imagery with a resolution of $2pix/cm^2$ and a DEM resolution of $11pix/cm^2$. Although we could not explicitly accomplish all of our milestones, we were still successful in the fact that we built and configured a working fixed-wing solution that could record imagery, albeit not yet autonomously. We hope to further test and improve on this aircraft, such that it can be realistically used as a solution to the challenges that we face with quadcopters.

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