THE UNIVERSITY OF MELBOURNE

Capstone Project

Final Report

2015

Project Title: Hybrid UAV Development for Emergency Response

Date: 18/09/2015

Project Team Information

Identifier:	**CP-CBU-155**	
Student workers:	Matthew De Bono	390758
	Alexander Daraio	389844
	Wesley Lim	391053
	Shanon Loveridge	218041
Academic supervisor:	Colin Burvill	
Academic examiner:	Saman Halgamuge	
Industry Mentor:	Jonathon Manton, DEEE	
Version:	1.0	

Acknowledgements

Team CP-CBU-155 would like to make the following acknowledgements:

- **Dr Colin Burvill**: for guiding and supporting us throughout the year.
- **Andrew Nolan and Jeffrey Hollingworth**: for their expertise, advice and generous equipment loans.
- **Phoenix Multicoptor teams**: for the laughs, advice and co-operation throughout the year.
- **Melbourne School of Engineering**: for workspace to complete our project.

Make sure to uncomment line here to generate Table of Contents, then comment out again

Contents

1 Executive Summary

COMPLETE THIS SECTION LAST

The Executive Summary offers a succinct statement of your findings and contributions.

It will summarise the project description and your contributions to the associated discipline.

This section can be based on key sentences and paragraphs from your Scope of Works and Progress Report documents, and your Conclusions and Recommendations section.

No more than five pages of text and images.

2 Introduction

This project is titled "Hybrid UAV Development for Emergency Response". This project is being completed under MAS (Melbourne Autonomous Systems); MAS is the official entrant into the UAV Challenge Medical Express 2016. The project entails the design and development of a novel, hybrid UAV, which is capable of autonomous flight .

The primary objectives of the project were the following:

1. Develop a UAV system to meet the requirements of the UAV Challenge
2. Achieve a functional UAV prototype, to be developed further in 2016
3. Introduce design novelty

A successful UAV capable of search and rescue applications will incorporate the following features:

- Payload receipt and transportation back to base
- Automated target identification of an uncommon (non high-visibility) target
- Capacity to switch between Vertical Take Off and Landing (VTOL) and traditional fixed-wing flight modes
- Capacity to switch between automated and manual flight modes through user commands
- A total flight travel distance of at least 60km
- A total flight duration of at least 60 minutes

This years team was tasked to provide a solid starting point for which next years team can build upon to realise the challenge requirements and goals. Specific deliverables were selected by the team to develop throughout the year in order to realise UAV Challenge objectives.

- **Transition System:** The development of a novel transistion system which allows the aircraft to switch between VTOL and fixed-wing flight modes
- **Flight Autonomy:** The development, documentation and implementation of automated flight controls
- **Object Detection and Avoidance:** The development of a low-cost medium range sensor system to enable object detection and path routing

WHAT DOES OUR AIRCRAFT BRING TO THE RESEARCH COMMUNITY

- Low cost autonomous aircraft
- Hybrid flight modes
- Long range AND long flight time in a single unit
- Intelligent drone flight (not just "follow me" behaviour)
- Uncountable applications beyond medical transport

3 Literature Review

This section will summarise and analyse the literature sourced and reviewed for your project.

This task should have been mostly completed when you completed your Progress Report #2 presentation.

This section and the associated Bibliography should be directly transferred from your Progress Report submissions.

Include the Samsung aircraft to the lit review list

Since PR1:

Firmware: https://github.com/diydrones/ardupilot (used as a base for our opensource firmware) http://dev.ardupilot.com/ https://pixhawk.org/dev/start

SetUp: http://copter.ardupilot.com/

Transition: https://www.youtube.com/watch?v=SZFagyigkPI (like the firefly 6)

4 Summary of UAV Challenge

The UAV Challenge is a competition held every 2 years where teams enter their UAV for the purpose of completing a autonomously search and rescuse type task. This iteration of the challenge is titled "Medical Express 2016", whereby teams are tasked with using an unmanned aircraft to fly out to a known area through specific transit corridors, search and correctly identify "Outback Joe", land close to him, have Joe place his simulated blood sample within the aircraft and then have the aircraft fly back to base such that his blood sample can be analysed.

The time period of the competition extends from registration (before 2nd September, 2015) to final competition (week starting 19th of September, 2016), spanning over 1 year. The following table highlights the key dates and corresponding events of the 2016 UAV Challenge.

Add completed to D1 once we get the response

Events	Date
Registration and Deliverable 1: Short Technical Report	2nd September 2015
Deliverable 2: Technical Report and Video	13th April 2016
Deliverable 3: Autonomous Flight Record	3 August 2016
Final "Go/No-Go" decision for teams	10 August 2016
Medical Express Challenge	Week starting 19th September 2016

5 Formulation of Design Requirements and Constraints

The design requirements and constraints of the project are determined by following the performance, deadline and safety requirements of the 2016 UAV Challenge, and also self-imposed constraints and requirements. For this task the required flight time, distance and maximum weight for a classification were selected as the starting parameters for the calculations.

Secondary objectives included the prioritization of low cost development, as well as use of readily available components and materials. The ranking of the priority of objectives is define as follows:

- **High Priority:** Primary objective of the project.
- **Medium Priority:** Objectives that result in performance specifications (treated negotiable).
- **Low Priority:** Not of primary concern, but to be addressed where feasible.
- **Competition Priority:** Important objectives to compete in competition, but out of this years scope.

The formulation of objectives, requirements and constraints provide the performance specificiations that are used as a foundation for the selection of motor, propellor and battery components. Everything required, and what we have covered this year (wes,matt,shanon,alex)

Table 1: Project Objectives for CP-CBU-155

Objective	Criteria	Priority
Compete in UAV Challenge 2016		
Register in UAV Outback Competition	Pass/Fail	High
Submit and Pass UAV Challenge Deliverable 1	Pass/Fail	High
Achieve a functional UAV		
Achieve maiden flight	Pass/Fail	High
Achieve autonomous flight	Pass/Fail	High
Adhere to UAV Challenge 2016 rules		
Be able to take off and land in obstacle rich environment	Pass/Fail	High
Introduce design novelty		
Introduce transition system between VTOL and fixed-wing modes	Pass/Fail	High
Utilize 3D printed components	Pass/Fail	High
Adhere to UAV Challenge 2016 rules		
Ability to take off and land in an obstacle rich environment	Pass/Fail	High
Ability to travel at least 60 kilometers	Pass/Fail	High
Ability to complete competition in at most 60 minutes	Pass/Fail	Competition
Other		
Manufacturable with available resources	Pass/Fail	Low
Manufacturable with readily available components	Pass/Fail	Low
Low cost project	Total Expediture (AUD)	Low
UAV transportable via car	Pass/Fail	Low

6 Aircraft Design and Implementation

- Basically PR1(prototype/printing/etc) (WES)
- Extra stuff... legs, new gears, glued on parts and changed placements for wings(Alex))
- testing:validation(how we knew we could fly), iterative design (designs changed through testing (like the back gears)), and problems (like the motor, power module and radio, their effect, and how they were resolved), link to diary (as there were significatn set backs)...
-
  - when we started flying really low (wes)
  - machines and mechanisms we tested on to make sure it wouldnt break (wes)
  - flight tests and tweaks in courtyard (wes)
  - major flight tests that worked well (july 3 and September 6)
  - Tuning
  - Data LOGS!!!
  - Major crashes and broken parts (Either don't include this, or frame it in a positive note. We can't have a section on failures.)
  - final transition

6.1 2014 Design

6.2 Configuration

A Y-3 configuration was selected over a Y-6 configuration, as it would lead to a lighter and cheaper aircraft. However, the aircraft was designed to be capable of being 'upgraded' to a T-6 configuration if the need arose.
Three motors would provide lift in VTOL mode, the front two motors being mounted vertically utilizing a mounting system capable of being rotated forwards 90° to facilitate the transition system and fixed-wing flight. The rear motor mount system was designed to be tilted laterally through the use of a servo-motor to enable the yaw mechanism of the aircraft.

In order to enable proper stable and robust mounting of all motors and mounting systems, custom prototyping using 3D printed parts were designed to fit within the X-8 flying frame. The major components of which are split up into the 'Motor Mounts', 'Front Mounting System' and the 'Back Mounting System'.
The Motor Mounts were designed to secure each motor to the mounting poles. The Front Mounting System was designed to incorporate the transition system, while also being stable enough to withstand disturbances Back Mounting System needed to incorporate the yaw servo-motor system

mention optimal 3D print orientations were investigated to strengthen against most possible failure modes.

6.3 Design Plan

basically how we intend to meet every requirement for the challenge. Put in circuit diagrams here, information regarding long range network transmitters, and basic intro to sensors, automation and transition. Basically introducing what the overall plan looks like and what we have covered from that. Maybe do a chart or table or something

6.4 3D Printing

6.5 Calibration

6.6 Testing

7 Autonomous Flight

- Can possibly merge this with another section
- Introduce the various flight modes (VTOL [Take-off and landing], Fixed wing [Main flight mode], Search [Identify Joe] for later sections

8 Sensing

Figure 1 outlines the on-board sensing capabilities that will be available to the aircraft. The sections below detail the use of each sensor during a mission, and are separated according to the different flight modes introduced in Section **??**.

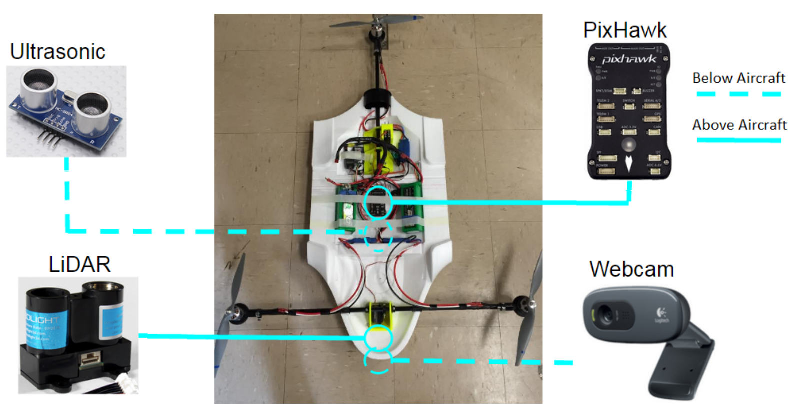

Figure 1: Onboard sensing capabilities for Prototype #1

8.1 All Flight Modes

Raspberry Pi

The Raspberry Pi will act as the aircraft's on-board computing platform, providing autonomy by giving flight commands to the flight controller, as well as the processing and intelligence for path planning, and object detection. It will also pull flight data from the PixHawk and other sensors, and generate detailed flight logs for later review.

PixHawk Flight Controller

The PixHawk will control the aircraft's flight functionality, such as controlling motors and ailerons, and executing flight paths and commands from the Raspberry Pi.

8.2 Vertical Take-Off and Landing

Ultrasonic Module

The ultrasonic module will be mounted underneath the aircraft. The GPS and altimeter will provide altitude measurements during fixed-wing flight; the ultrasonic will augment these by providing a more reliable and controllable height measurement during rotor-based flight, assisting with search and landing.

8.3 Long Range Flight

PixHawk Sensors

It also has several in-built or plug-and-play sensors, including a 3-axis accelerometer, altimeter, compass, and GPS. The PixHawk will provide the aircraft's telemetry to the Raspberry Pi and the base station, which will be augmented by the additional sensors below.

8.4 Finding Joe

Webcam

The webcam will be mounted beneath the nose of the aircraft. It will provide vision for the aircraft's obstacle avoidance manoeuvers, and will form the basis for identifying Joe using his hat and blue jeans.

LiDAR

The LiDAR will be mounted in the nose of the aircraft. The LiDAR can only measure the range of objects directly in front of it, so it will be mounted on a dual servo system that allows it to sweep a hemisphere in front of the aircraft (see Figure 2). It will provide a 3D map of the environment in front of the aircraft, and will assist in path planning and obstacle avoidance.

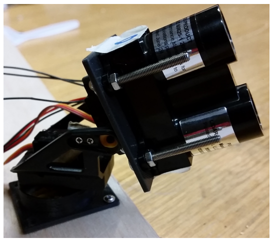

Figure 2: LiDAR mounting

9 Planning - Finding Joe

-fill this part out with all the stuff that is and isnt tangible that youve been doing (shanon)

9.1 Object Detection

In order for the aircraft to safely navigate while searching for Joe, it must first know where it is safe to move in the environment. State-of-the-art autonomous vehicles commonly use Red-Green-Blue-Depth cameras, allowing them to get both visual and depth/distance information simultaneously; while these cameras are powerful, they are also expensive. Instead, a low-cost option combining data from the camera and LiDAR sensors shown in Section 8 was chosen to approximate an RGB-D camera.

Object detection is initiated once the aircraft reaches the remote landing site. Figure 3 shows the progression of data acquisition using the LiDAR.

Elaborate:

- Initially empty occupancy map (Figure 3a)
- LiDAR identifies distances from aircraft, which are converted to “occupied” cells/voxels in the map (Figure 3b)
- Once a reasonable amount of data has been acquired (Figure 3c), the map is filtered to eliminate “isolated” voxels
- The resulting map is then grouped into “supervoxels”, large areas that the aircraft cannot traverse

9.2 Path Planning

Planning module takes the occupancy grid, then generates a flight path the aircraft can traverse. Rescanning is performed if the aircraft moves out of the “known” area.

10 Transition

(alex)

- all the stuff done
- tests to prove it worked. Gyroscope equations
- Anything that broke as a result of not testing something, or anything that resulted in modification to Dragonfly, write it as if we performed a test, then made the change, rather than “oh that broke, what happened?”
- information pertaining to future test flights

10.1 Why Transition?

In order to complete the objectives, long range flight would be required. This is why a transition system was necessary to implement, allowing the VTOL drone to fly forwards, both faster and more efficiently. This will hopefully allow the drone to fly for the required 1 hour flight time needed in deliverable 2, and allow it to travel for over 60 km that is required for the task.

10.2 Parts

The plane was designed from the beginning to deal with transition. What was decided was that two propellers of the VTOL copter would rotate forwards, creating a forward thrust and generating lift on the wings. Before implementation however, a few physical considerations needed to be thought through.

Firstly, a combination of wings and front motors capable of flight were required. For this the Skywalker X8 seemed to be a commonly used drone that worked well, and the motors chosen (Turnigy SK3-3542-800) were the same ones chosen by others online user some who have achieved over 142km of flight with the Skywalker(link?). To ensure that it would definitely not stall mid-flight, the motors were checked on e-calc [PUT IN APPENDIX REFERENCE TO ECALC], and they had an estimated stall speed of 32km/h with this combination, and a cruising speed of 82km/h. The performance was also compared against other motors.

(a) Initial (empty) environment

(b) 10s of data acquisition

(c) 60s of data acquisition

Figure 3: Scanning the environment with the LiDAR

10.3 Gyroscopic Forces

An analysis of the gyroscopic forces acting on the motors during transition was needed to be done to determine the configuration of rotating motors, the strength of the shaft in between the two motors, and the torque required to make the transition. The calculations (see A) showed that gyroscopic forces would create a moment perpendicular to the direction of rotation based on the direction of the motor angular velocity. To counteract this, two propellers on the front spinning in opposite directions would create zero net moment, and therefore the drone would be able to remain straight after transition. This was already the plan as counter rotating propellers also create a zero net angular momentum from the front in VTOL mode, making control much easier. From this, the total moment created by this gyroscopic motion was 3.1Nm in the centre of the shaft, however for our rotation speed, this was less than the moment gravity exerted on the shaft while the motors were hovering, which was 9.156Nm. Lastly, the transition system would need to hold the propellers steady for any other gyroscopic forces. In particullar if the plane rolls too fast, it would create a moment in the front. Due to the counter-rotating front motors however, these forces again would be opposite and counteracting. The front servo would therefore receive no counter moment in flight. An arbitrary servo was chosen at 9kg/cm (0.88Nm), through testing it was found behave satisfactory against frictional or other unknown forces. This was verified by holding the drone down in tests and ensuring transition was possible at full motor speed.

10.4 System Design

For implementation a 1:1 gear system attached to the servo and motor shafts was installed [PHOTO OF SYSTEM]. This allowed for full rotation of the servo, and maximum accuracy. Through testing of PWM values, it was set up to rotate by 90 degrees as required. A new mode was created through the open source Pixhawk firmware called FixedWing, and possible transition from the VTOL modes was also set-up. This was created so that when a switch on the controller is turned on the front motors rotate forwards, the VTOL control systems turn off, and the fixed wing control systems take over. So far, a manual fixed wing mode has been created. It changes the controls from controlling the rotation of the multi-copter, to the control surfaces of the plane when entering this mode. In order to implement this, changes to the firmware were required. This meant having a complete understanding of the programming behind both the Pixhawk and the open source ardupilot project, and it also meant we contributed to this open source platform. Eventually other modes would need to be created to complete the task, such as automated modes, or modes with basic stability control.

11 Remaining Sections

You are welcome to choose appropriate names for section headings.

The main argument will begin with a section describing your team's major activities, leading to the fulfillment of the objectives of your project. A flow chart will provide a useful visual aid.

Introduce the tasks that you were required to complete to satisfy the agreed project scope. Itemise tasks whenever possible to assist cross-referencing with following sections (i.e. your contributions).

Describe the development your ideas and strategies, the conceptual design and research methods used (as applicable), and why they were chosen (your literature review will be of value here).

Discuss any original contributions including, for example, modifications or extensions of published methods or associated knowledge. Your team may have made a more humble, but still valuable, contribution, where you customised an existing method for your specific application. Describe the benefits and, if applicable, deficiencies associated with your contributions.

The criteria against which preferred concepts are identified should be discussed. This aspect of your report, appropriately sectioned, will make extensive use of pictorial information (figures) and organised information (lists and tables).

Given Final Report submissions are normally not paper-based, all supporting material (figures, tables) in the main body should be easily read on a standard computer screen, for example: Text/font size should be consistent, Do not change from portrait to landscape orientation Maintain A4 size (i.e. no fold outs to accommodate A3 size) Appendices can include different page sizes to accommodate, for example, large-format Gantt charts.

The details of completed analyses and supporting calculations can be included in an Appendix, referred to, as required, from the main body of the report. Summaries, flow charts identifying methodologies, and sample calculations should be included in the main body of the report.

The process that you developed and then used to facilitate specific contributions may, itself, be one of your contributions (i.e. providing a framework for ongoing work by other practitioners or researchers). This is worthy of inclusion as a section of the main body of the report.

12 Conclusions and Recommendations

12.1 Achievements

12.2 Further Work

12.3 Recommendations

Confirm that the objectives stated in the Introduction have been met. If the objectives in the Scope of Works document have not been fully met, an argument is required as to why the outcomes do not correspond with those envisaged.

Opportunities for further work, identified through the activities of the current project but outside its scope, should be identified.

This section will summarise your teams final response to the initial question, problem or issue. A summary of the arguments associated with your outcomes will be provided so that the reader is aware of your reasoning.

Do not include any personal responses to the project (eg. ...we enjoyed working with Joe and learnt a lot from Jen...). Write this report as if you are a professional practitioner, representing a research organization or consulting design bureau.

You are encouraged offer details of successful task completion. Success can be interpreted in many ways, for example: Team CP-xxxx contributed X to the overall Y research program led by Professor Z The client mentor was satisfied with the alternative conceptual designs offered by team CP-xxxx The leader of the research division of the collaborating organisation was impressed with the alternative experimental method proposed by team CP-xxxx An extensive review of the scientific literature has been completed by team CP-xxxx Commercially available solutions were identified and ranked against criteria developed in conjunction with the client

You can report on the status of your contributions. For example, within the collaborating research laboratory, research group, research initiative, or client company, the final proposals of team CP-xxxx: have been implemented, are under review for later implementation, are awaiting detailed costing, or have provided a range of novel alternative strategies for later consideration.

Do not apologise. Focus only on the positive outcomes of your work. As an example, it is likely that tasks identified in your Scope of Works but not completed would have required more resources than were available. Identify important tasks not completed as opportunities for further work within the associated DME laboratory or client organization, and discuss why they are important. Given the many tasks that you have likely completed, your team now have an excellent knowledge of the requirements of the tasks not completed briefly outline your expectation of the resources (i.e. personnel expertise, equipment, facilities, finance) needed to complete important tasks.

A Stuff

Detailed work completed by the project team not included in the main body (calculations, sketches, details of activities not suited to the main body, e.g. raw data from experiments).

Gyroscopic Effects:

Angular momentum of propellers: $H = I\omega$
Maximum motor speed $\omega = 800 \times 16.8 \times 2\pi/60 = 1407.45 rad/s$
Prop Inertia $I = 1/12 \times M(L^2 + B^2) = 1.16 \times 10^{-4} kgm^2$ (Overestimate, as it assumes equally distributed mass, and constant width)

[diagram above] Using a small angle approximation $\Delta H = \omega_p \times \Delta t \times I \times \omega$
$\omega_p =$ Maximum servo rotation speed (procession) $= 60^o/0.11s = 9.52 rad/s$
$dH/dt = \omega_p \times I \times \omega = M = 1.55 Nm$

- [diagram above] Counter-rotating propellers stop the drone from yawing (and possibly spinning out of control on transition), as the moments act in opposite directions. They also act to make gyroscopic forces on the servo negligible due to them counteracting each other in a twist motion when the drone rolls fast, instead of putting a moment on the servos.
- Max moment in the centre of the front shaft is $2M = 3.1 Nm$. If this is less than the moment on the front bar at hover ($2/3 \times$ mass of drone $\times$ distance to prop) then the shaft should be capable of withstanding the gyroscopic effects.

For our set up this is the case as the gyroscopic moment is less than the weight of the plane on the front shaft $3.1 Nm < 9.156 Nm$. If it can withstand the weight, it should be able to withstand the gyroscopic moments easilly.

B Something

Management and administration information: Gantt chart (schedule) Include important issues associated with task duration prediction presented in your Progress Reports. Cumulative hours spent on project individual and/or team based, project diaries, meeting minutes or summaries (i.e. useful outcomes from each meeting). Each meeting will require a numeric identifier if you are to reference expert opinion in the main body of your report (eg. Section A.2.3). Individual or team based project diary. Copy of your final Scope of Works.

-Shanon can you do gant stuff? -[Lets get a list of all trello jobs submitted here (when they were completed etc). This can be out diary]

C Test

Existing Aircraft

Figure 4: Arcturus Jump, taken from http://www.arcturus-uav.com/aircraft_jump.html

Figure 5: X PlusOne, taken from
https://www.kickstarter.com/projects/137596013/x-plusone-your-ultimate-hover-speed-aerial-camera

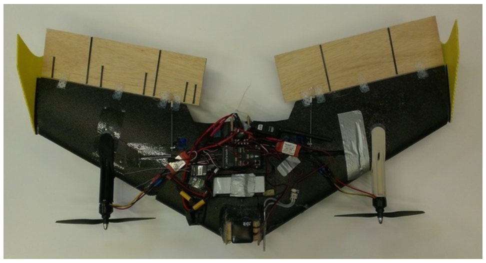

Figure 6: TBS Caipirinha, taken from https://pixhawk.org/platforms/vtol/tbs_caipirinha_vtol

Add Samsung aircraft

D Analysis of 2014 Model

Figure 7: FireFly6, taken from `http://www.robotshop.com/ca/en/firefly6-vtol-y6-multirotor-drone-frame.html`

Research suggests that a Y6 configuration, with 3 sets of 2 coaxial motors (2 pairs at the front, 1 at the rear), is the best setup for this task, as shown on the FireFLY6 in Figure 7 above. However, due to its weight and construction, this is not possible on the 2014 model. Instead, it will have to be fitted in quadrotor formation, with four motors and rotors attached under the fuselage (Figure 4). To hover the aircraft (22kg) with 4 (3.5kg) motors equipped with 10cm propellers, in air with density 1.168 kg/m3 would require

$$P = v_{air} * F_{thrust} = \sqrt{Fthrust/(\rho_a ir * \pi * r_p rop^2)} * F_t hrust = F_t hrust^{3/2} / \sqrt{\rho_a ir * \pi * r_p rop^2} = (mg)^{3/2} / \sqrt{N_m otors^3 * \rho_a ir *$$

This requirement is per motor, under ideal conditions (100 percent motor and rotor efficiency). A cost effective motor for this is the Turnigy RotoMax, which cost 90AUD on sale at HobbyKing, bringing the cost of motors alone to 360AUD. However, more significant is that 75A is required per motor (combined current of 300A) along with a 10 cell (3.7V) battery. The most cost effective battery at HobbyKing capable of this is the Turnigy Nano-Tech 4400mah Lipo Pack at 81AUD. With 4 motors at 75 Amps, this battery will last approximately $t_{batt} = 36004400/475 = 53s$

Assuming a single take-off/landing manoeuvre can takes at most tbatt, we would require four batteries to complete the challenge, costing 324AUD in total, with total extra weight of 4.8kg. However, we would require even more power to complete the fixed-wing, 10km flight to find Joe.

In addition to cost, the modifications necessary to make such a plane would be significantly harder, as the supports would need to hold a lot more weight, and the plane itself is made of wood and not foam. The design of the craft (as both a quadcopter and fixed wing aircraft) on the larger craft would have a significant amount of aerodynamic drag and be less efficient.

Last years project was designed with a separate scope in mind, with a very different challenge where VTOL was not required It was also designed as a multi-platform craft, where the fixed wing was designed to manufacture, something we certainly dont plan on doing this year with the wing. With consideration to all of the above points, we believe that purchasing a foam model airframe to build off is the best course of action for the 2015 development.

Add references for Bibliography