Fall 2015

From Quadcopter to Submarine

Everett C. Brown II
Washington University in St Louis

Juan Matheus
Washington University in St Louis

Sam Gardner
Washington University in St Louis

Recommended Citation

Brown, Everett C. II; Matheus, Juan; and Gardner, Sam, "From Quadcopter to Submarine" (2015). *Mechanical Engineering Design Project Class*. 41.
https://openscholarship.wustl.edu/mems411/41

MEMS 411 Submersible Drone

From Quadcopter to Submarine

Everett Brown
Juan Matheus
Sam Gardner

The goal of this project was to create a quadcopter that is capable of going underwater and returning to the surface to take off again. This concept was created after speaking with a customer that had very specific user needs. The project included creating several different designs and doing a concept selection based on these user needs. After selecting a concept, a design was created and adjusted based on an engineering analysis. The parts were selected based on a budget that was assigned to the project and a prototype was created. The final prototype was capable of flight and was completely submergible, however; the static stability of the craft prohibited flight after returning to the surface of the water.

Department of Mechanical Engineering and Materials Science
School of Engineering and Applied Science
Washington University in Saint Louis

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Project Problem statement

Drones and UAV (Unmanned Aerial Vehicles) have been gaining popularity in the last few years. They have gone from being military grade technology to mass consumer gadgets in a fairly short time period. Alongside with the availability of ready-to-fly drones at reasonable prices, a trend of home-built drones has proven the technology is not only simpler than what it may seem but it also poses an engineering design problem due to the wide array of applications drones may have.

Since one can purchase a kit from a manufacturer and put it together, the Mechanical Engineering Senior Design Project idea was to create an add-on to a drone that could either be purchased or built in house. The process involved interviewing faculty, which served as the main user to find out unmet needs that could be satisfied by incorporating new functionality to a drone. Out of the series of conducted interviews, it was brought to the team's attention that it could be useful to have a drone that not only would be waterproof, but could potentially submerge in water.

The idea was appealing to the team because it was innovative and it haven't been done before. Research suggested tech-savvy people have succeeded at waterproofing drones that could land in water by using air flotation devices but a homemade drone that was able to go underwater was something the team could not find.

During the concept generation the team looked into various possibilities to make the drone sink, as well as the overall construction that would be able to keep water out of electrical components. A submarine came to mind and research on how they operate suggested a ballast system of some sort was the solution to the problem. The concept changed several times as the team tried to optimize cost and reduce the number of parts. A piston driven ballast seemed challenging due to the use of gears and electric motors that needed to be underwater so it had to be discarded as a plausible solution. A more cost-effective and simpler ballast concept was created using water pumps, typically used in garden fountains or aquariums. The rest of the drone design revolved around the ballast system and since everything needed to be watertight, the body of the drone itself needed to custom made. There were some drawbacks of using this system but the benefits outnumbered the disadvantages. Those will be covered more in-depth throughout the report.

1.2 List of team members

Team Members:

- Sam Gardner
- Juan Matheus
- Everett Brown

2 Background Information Study

2.1 Design Problem

The popularity of drones and UAVs has increased dramatically over the past several years as an effective way of achieving a variety of tasks such as aerial filming, scanning, and even transportation of objects. However, all drone kits on the market are limited to aerial operation. Is it feasible to create a drone that can operated both in air and in water? The design problem wants a drone that can operate in air and water. A submersible drone creates another environment for the drone to interact with and a variety of new tasks for drones to perform. However, a drone that can maneuver in both mediums must first be developed.

2.2 Background information

Drone Codes and Standards

- https://www.faa.gov/uas/faq/
- https://www.faa.gov/uas/regulations_policies/
- http://www.howtogeek.com/213159/what-you-need-to-know-before-flying-a-drone/

3 Concept Design and Specification

3.1

Customer Needs Interview

Table 1: User Needs Interview

Project/Product Name: Submerging Drone			
Customer: Jakiela, M. Address: Washington University Willing to do follow up? Yes Type of user: Primary		Inteviewer(s): Brown, Gardner, Matheus Date: 9/16/2015 Currently uses: —	
Question	Customer Statement	Interpreted Need	Importance
What additional feature you want the drone to have?	I would like it to ideally be able to land on water and submerge	Waterproof, submerging drone	5
How deep should it dive ?	I'd like it to reach the bottom of a pool	Able to withstand a depth of about 3m	4
What's the desired flight range/time	30m altitude 500m radius 10min	Remote controlled drone with enough power, lift, range	3
Does it have to be reusable?	Yes	No design should consider the drone to be disposable	2
If it can submerge, would it be ok if it can just land on water?	If it can't submerge, I'd like a detachable submarine, less ideally it would work as a boat and even less preferred, it lands on water and takes off	Concept designs based on level of complexity	2

Table 2: Final User Needs

Need Number	Need	Importance
1	Drone depth of about 3m	5
2	Ability to take off/land on water	5
3	Ability to hold a camera	1
4	Easy to repair	2
5	Needs to lift 5lbs above its weight	4
6	Needs to be able to fly 30m high and on a 500m radius away (range)	3
7	It needs to be able to be reused	2
8	It should be able to drop an object on a target that's 3m deep	4
9	It should be easy to operate	1

Table 3: Identified Metrics

Metric Number	Associated Needs	Metric	Units	Goal Value
1	1	depth	meters	3
2	2	Binary	integer	1
3	3	Binary	integer	1
4	4	Number of custom parts	integers	10
5	5	weight (above empty weight)	kg	2
6	6	Time	minutes	10
7	6	Distance	meters	500
8	7	Binary	integer	1
9	8	Distance from target	meters	10
10	9	Number of controllers	integer	3

3.2 Concept Drawings

Figure 1: Concept Drawing 1

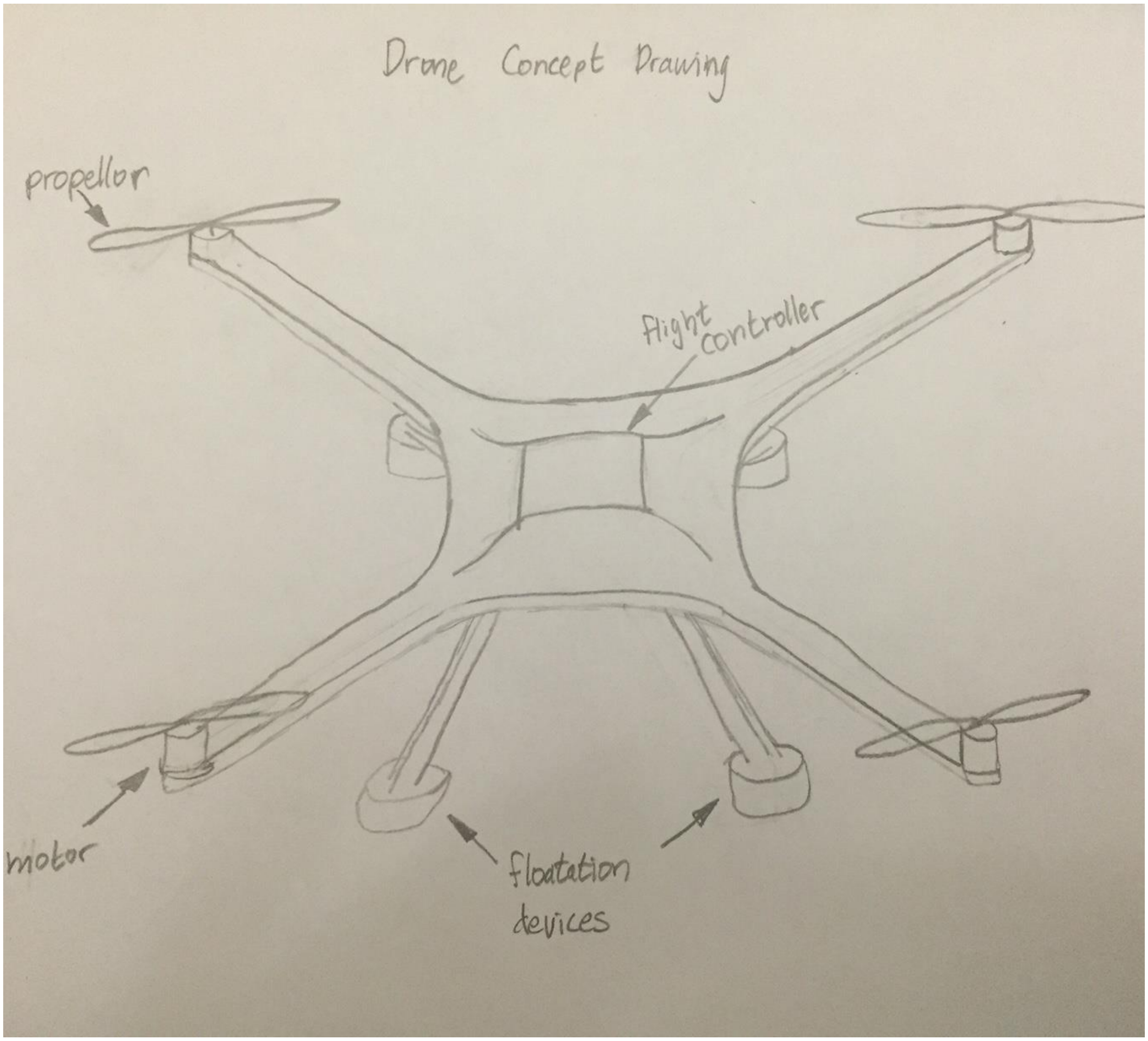
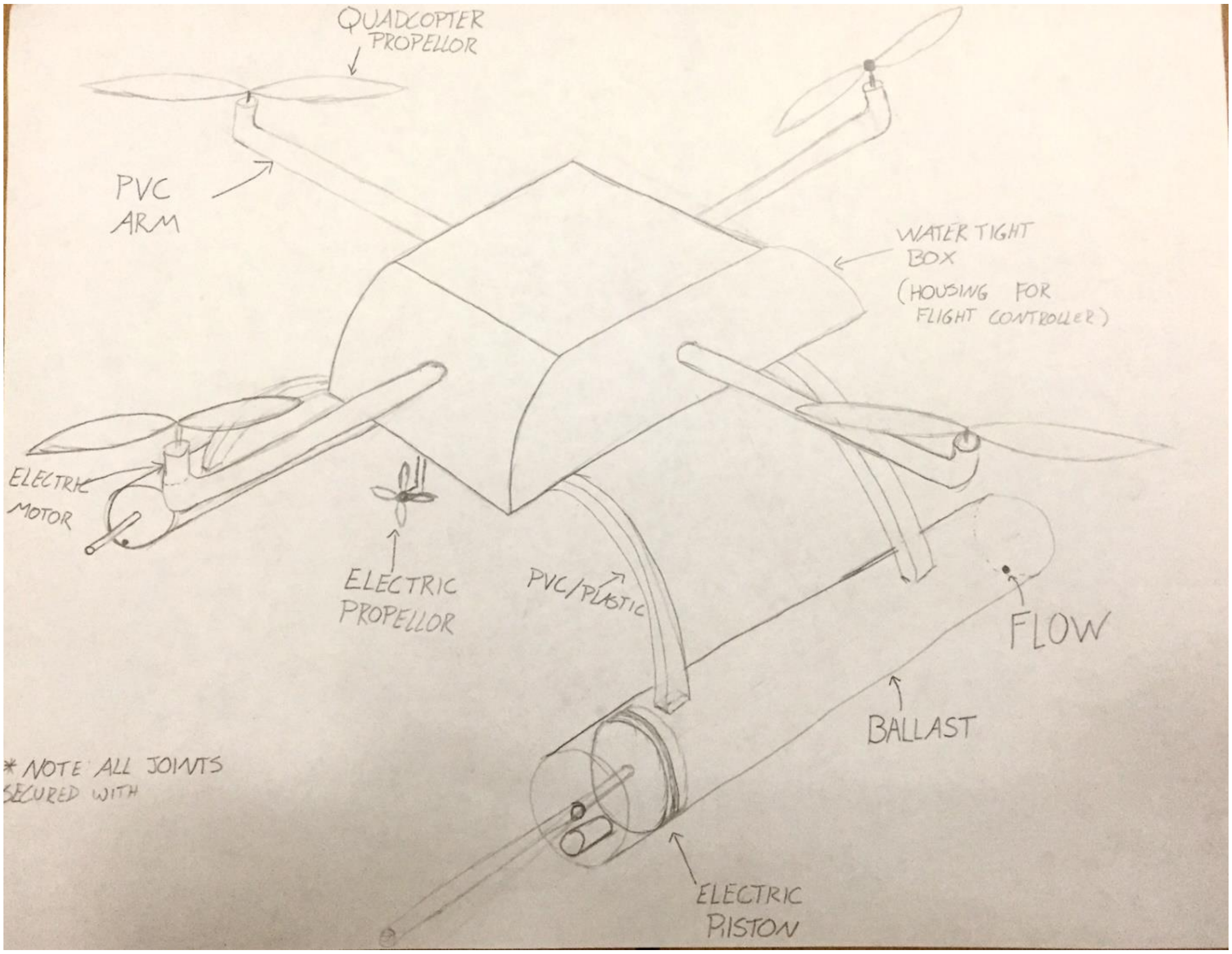


Figure 2: Design Concept 2



*NOTE ALL JOINTS SECURED WITH

Figure 3: Design Concept 3

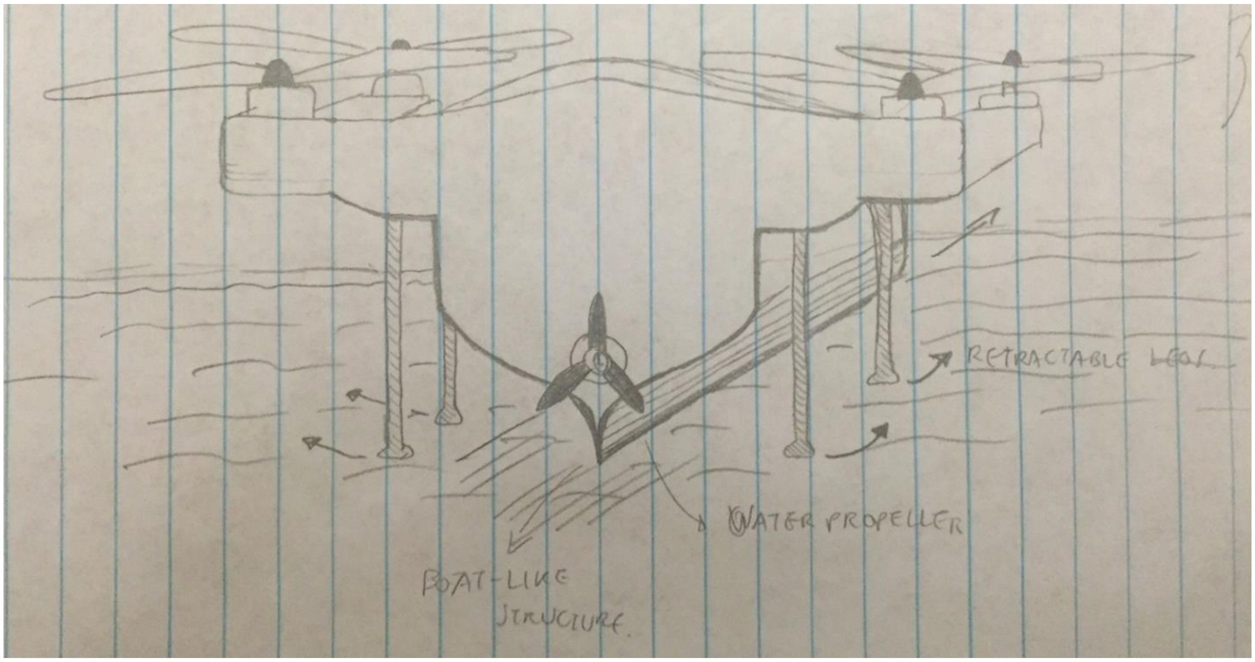
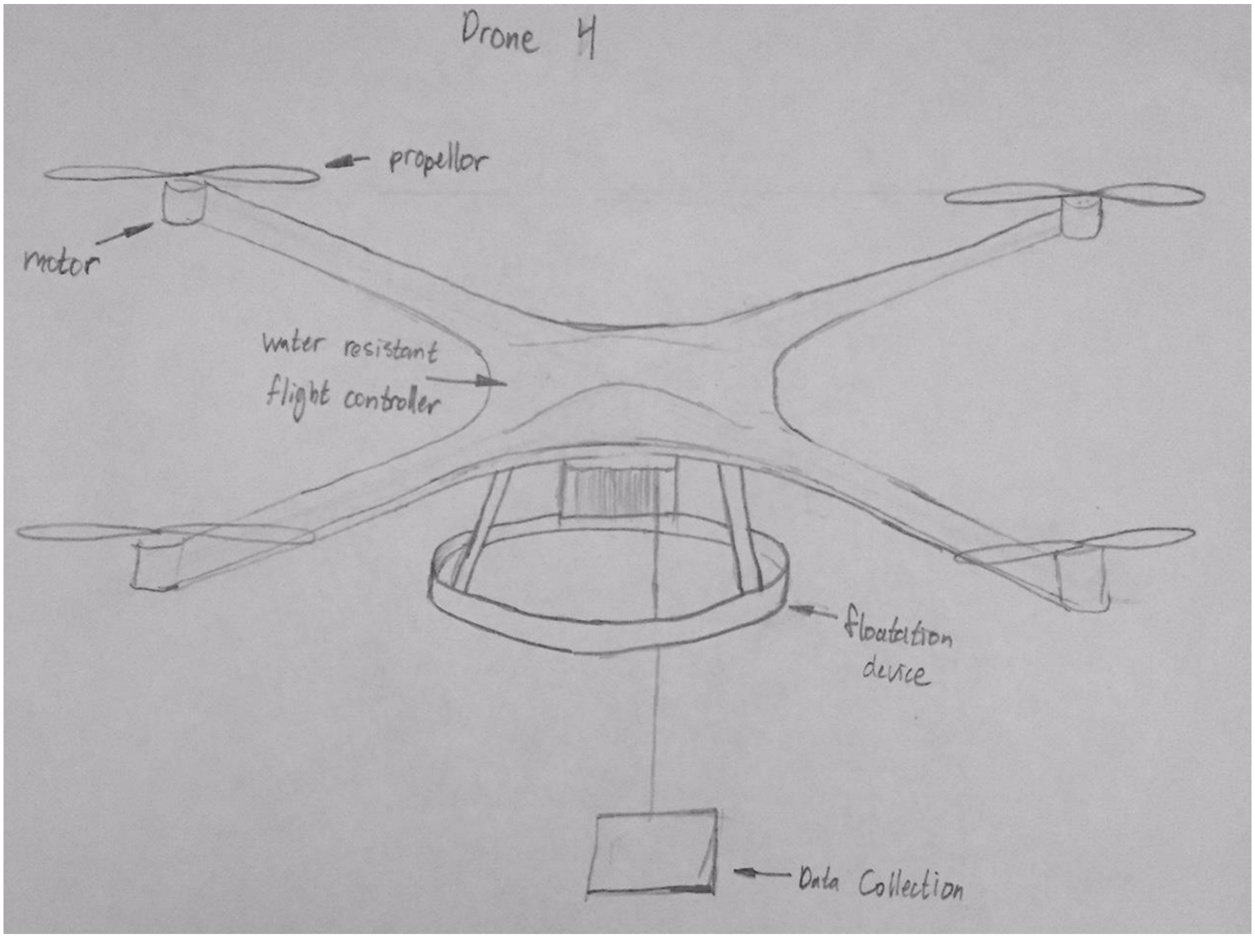
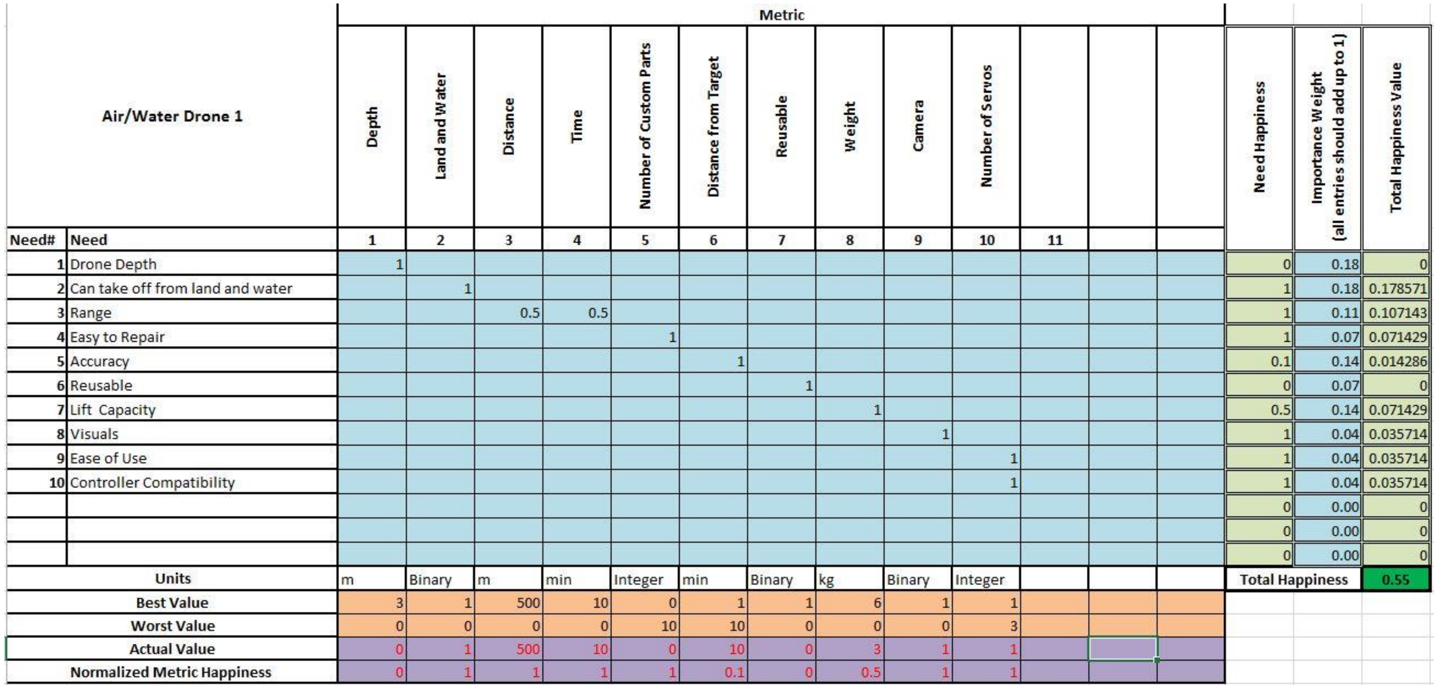


Figure: Design Concept 4



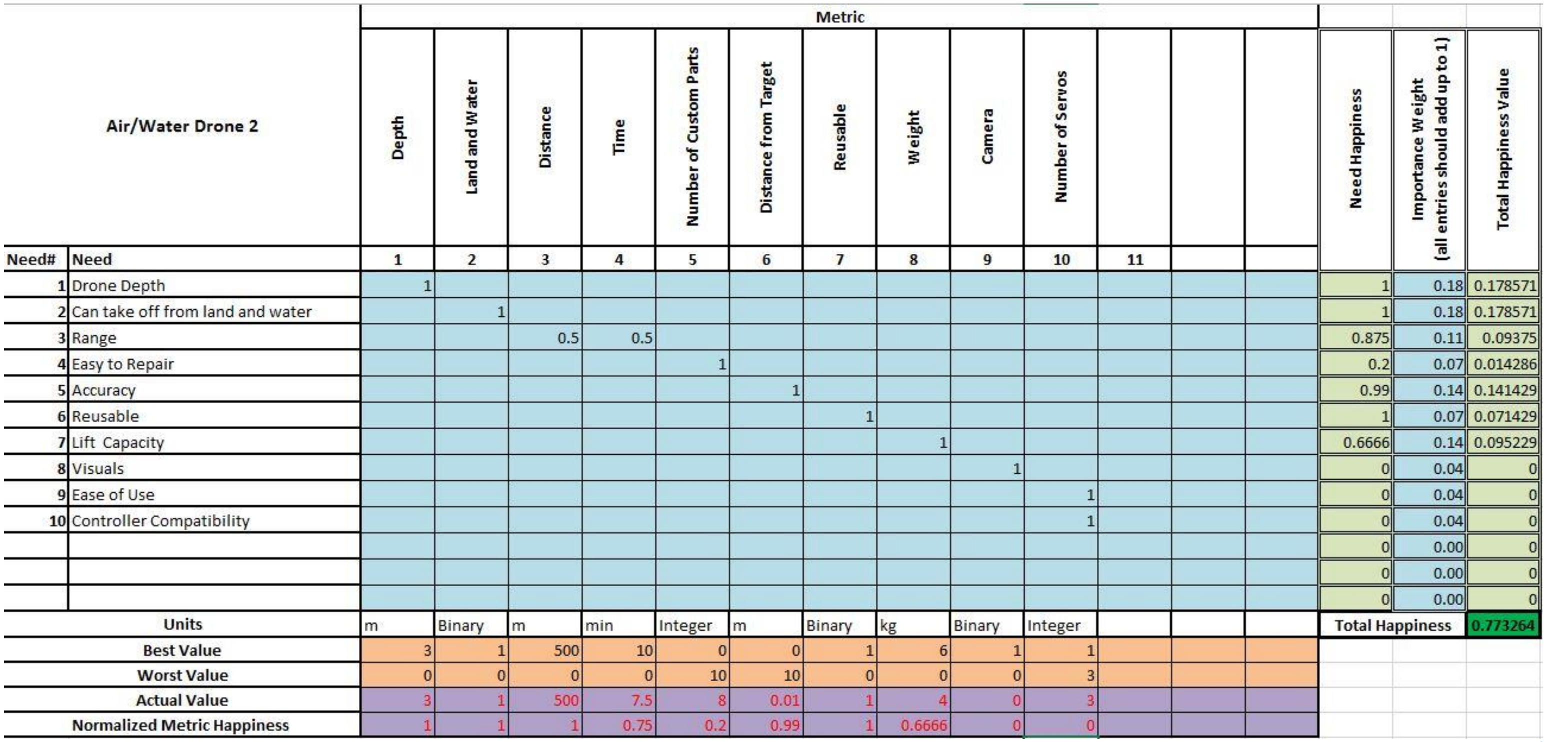
3.3 Concept Selection

3.3.1 Concept scoring



Air/Water Drone 1		Metric															
		Depth	Land and Water	Distance	Time	Number of Custom Parts	Distance from Target	Reusable	Weight	Camera	Number of Servos				Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11					
1	Drone Depth	1													0	0.18	0
2	Can take off from land and water		1												1	0.18	0.178571
3	Range			0.5	0.5										1	0.11	0.107143
4	Easy to Repair					1									1	0.07	0.071429
5	Accuracy						1								0.1	0.14	0.014286
6	Reusable							1							0	0.07	0
7	Lift Capacity								1						0.5	0.14	0.071429
8	Visuals									1					1	0.04	0.035714
9	Ease of Use										1				1	0.04	0.035714
10	Controller Compatibility										1				1	0.04	0.035714
															0	0.00	0
															0	0.00	0
															0	0.00	0
Units		m	Binary	m	min	Integer	min	Binary	kg	Binary	Integer				Total Happiness		0.55
Best Value		3	1	500	10	0	1	1	6	1	1						
Worst Value		0	0	0	0	10	10	0	0	0	3						
Actual Value		0	1	500	10	0	10	0	3	1	1						
Normalized Metric Happiness		0	1	1	1	1	0.1	0	0.5	1	1						

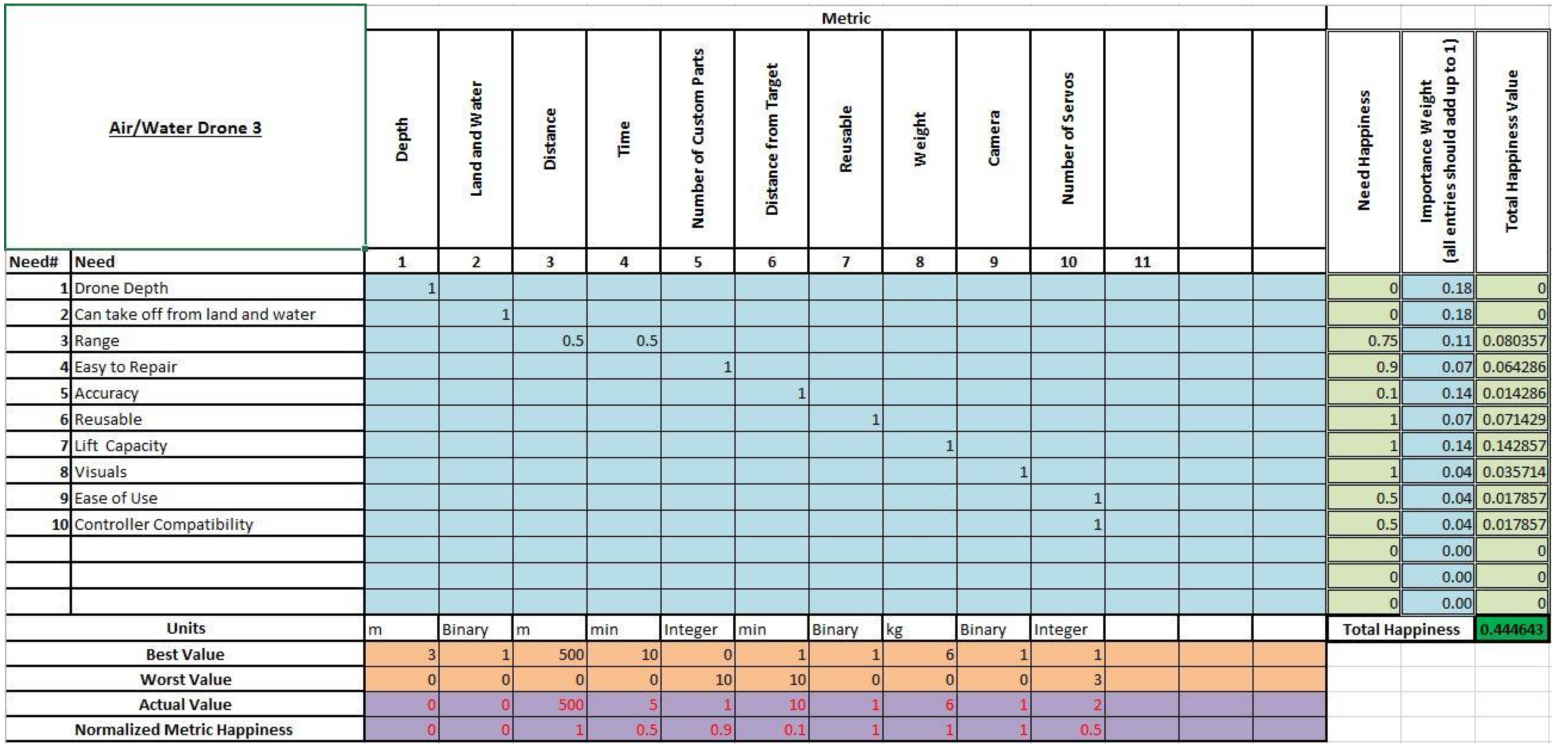
Figure 5: Scoring for Design 1



Air/Water Drone 2		Metric													Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
		Depth	Land and Water	Distance	Time	Number of Custom Parts	Distance from Target	Reusable	Weight	Camera	Number of Servos						
Need#	Need	1	2	3	4	5	6	7	8	9	10	11					
1	Drone Depth	1													1	0.18	0.178571
2	Can take off from land and water		1												1	0.18	0.178571
3	Range			0.5	0.5										0.875	0.11	0.09375
4	Easy to Repair					1									0.2	0.07	0.014286
5	Accuracy						1								0.99	0.14	0.141429
6	Reusable							1							1	0.07	0.071429
7	Lift Capacity								1						0.6666	0.14	0.095229
8	Visuals									1					0	0.04	0
9	Ease of Use										1				0	0.04	0
10	Controller Compatibility										1				0	0.04	0
															0	0.00	0
															0	0.00	0
															0	0.00	0
Units		m	Binary	m	min	Integer	m	Binary	kg	Binary	Integer				Total Happiness		0.773264
Best Value		3	1	500	10	0	0	1	6	1	1						
Worst Value		0	0	0	0	10	10	0	0	0	3						
Actual Value		3	1	500	7.5	8	0.01	1	4	0	3						
Normalized Metric Happiness		1	1	1	0.75	0.2	0.99	1	0.6666	0	0						

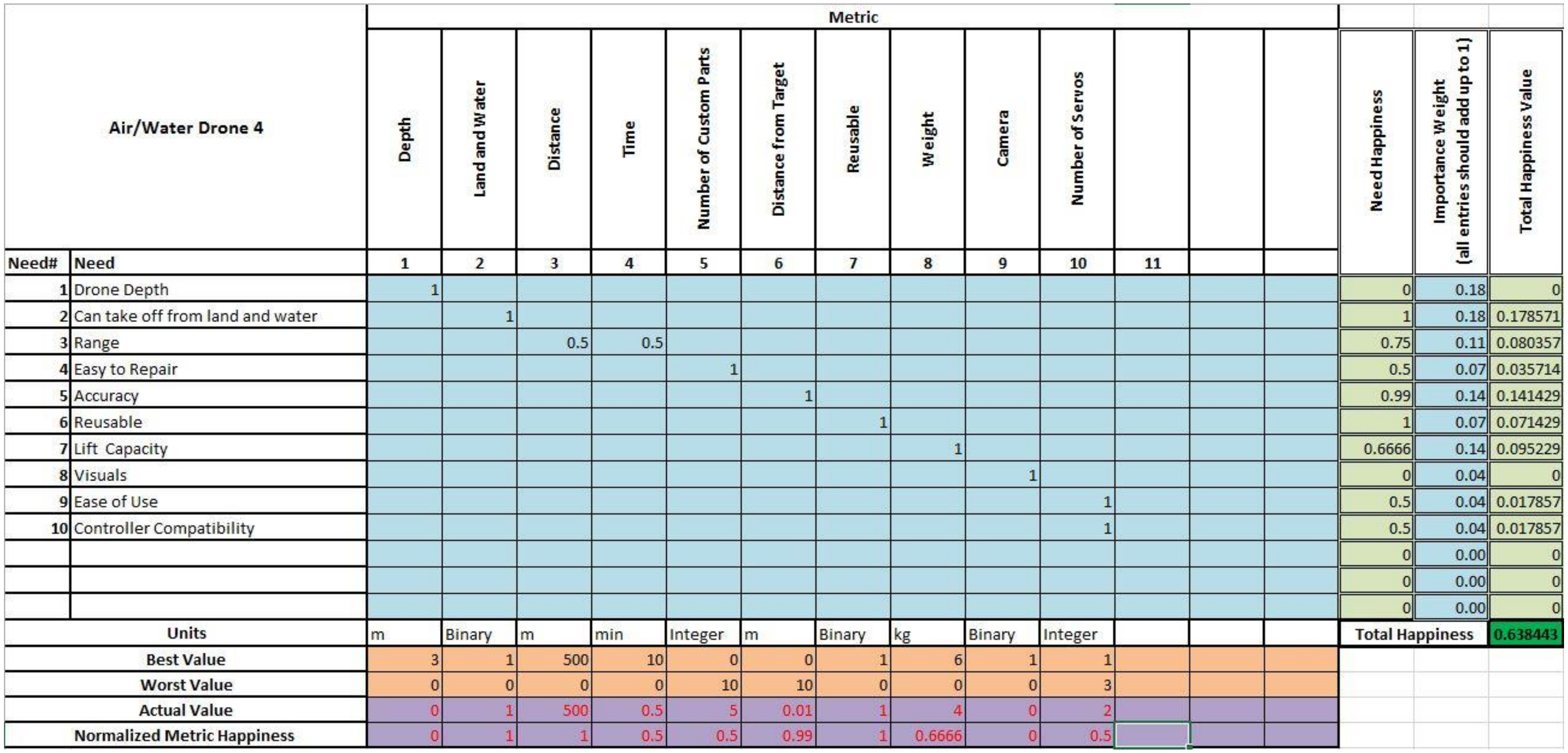
Figure 6: Scoring for Design 2

Figure 7: Scoring for Design 3



Air/Water Drone 3		Metric															
		Depth	Land and Water	Distance	Time	Number of Custom Parts	Distance from Target	Reusable	Weight	Camera	Number of Servos				Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11					
1	Drone Depth	1													0	0.18	0
2	Can take off from land and water		1												0	0.18	0
3	Range			0.5	0.5										0.75	0.11	0.080357
4	Easy to Repair					1									0.9	0.07	0.064286
5	Accuracy						1								0.1	0.14	0.014286
6	Reusable							1							1	0.07	0.071429
7	Lift Capacity								1						1	0.14	0.142857
8	Visuals									1					1	0.04	0.035714
9	Ease of Use										1				0.5	0.04	0.017857
10	Controller Compatibility										1				0.5	0.04	0.017857
															0	0.00	0
															0	0.00	0
															0	0.00	0
Units		m	Binary	m	min	Integer	min	Binary	kg	Binary	Integer				Total Happiness		0.444643
Best Value		3	1	500	10	0	1	1	6	1	1						
Worst Value		0	0	0	0	10	10	0	0	0	3						
Actual Value		0	0	500	5	1	10	1	6	1	2						
Normalized Metric Happiness		0	0	1	0.5	0.9	0.1	1	1	1	0.5						

Figure 8: Scoring for Design 4



Air/Water Drone 4		Metric															
		Depth	Land and Water	Distance	Time	Number of Custom Parts	Distance from Target	Reusable	Weight	Camera	Number of Servos				Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11					
1	Drone Depth	1													0	0.18	0
2	Can take off from land and water		1												1	0.18	0.178571
3	Range			0.5	0.5										0.75	0.11	0.080357
4	Easy to Repair					1									0.5	0.07	0.035714
5	Accuracy						1								0.99	0.14	0.141429
6	Reusable							1							1	0.07	0.071429
7	Lift Capacity								1						0.6666	0.14	0.095229
8	Visuals									1					0	0.04	0
9	Ease of Use										1				0.5	0.04	0.017857
10	Controller Compatibility										1				0.5	0.04	0.017857
															0	0.00	0
															0	0.00	0
															0	0.00	0
Units		m	Binary	m	min	Integer	m	Binary	kg	Binary	Integer				Total Happiness		0.638443
Best Value		3	1	500	10	0	0	1	6	1	1						
Worst Value		0	0	0	0	10	10	0	0	0	3						
Actual Value		0	1	500	0.5	5	0.01	1	4	0	2						
Normalized Metric Happiness		0	1	1	0.5	0.5	0.99	1	0.6666	0	0.5						

3.3.2 Preliminary Analysis of each Concept's Feasibility

Concept 1: Dropping from sky/surface

This is very close to the benchmark and what is readily available on the market today. The quadcopter design is tried and tested and can be completed with a variety of materials. The major drawback of this design is the lack of accuracy that it provides in delivering a package or material. GPS can be added but controlling the fall of a package through the sky and water would not be possible. The design to allow the quadcopter to float on the water is achieved by replacing typical landing struts with pontoon like structures. The mechanism that releases the package is a mechanical claw that can be opened and closed with an extra servos connected to the flight controller. Because of the simplicity of this design it can be versatile and easily repaired/fixed. The entire quadcopter does not necessarily have to be completely watertight which decreases the difficulty of manufacturability.

Concept 2: Fully Submergible

Concept 2 poses multiple significant design problems. The first problem is the waterproofing of the entire quadcopter. This can be achieved by constructing the arms and flight controller box out of PVC material and securing all joints with plumbing cement. The major drawback for this approach is that it makes servicing the internals of the quadcopter difficult once it is completely sealed. The second design issue is that of buoyancy. This is solved by making the landing gear out of a piston ballast system that can be manufactured from PVC and small electric motors. Finally, an extra propeller and motor need to be added to aid in underwater motion. One issue that arises with this design is that the extra motors require a more advanced control system that is capable of several channels of communication. Concept 2 would have the most accurate underwater delivery system because it would be able to move freely underwater and place packages exactly where desired.

Concept 3: Boat on water

Concept 3 poses the most difficulty in terms of manufacturability because the hull of the quadcopter/boat would need to be custom design and made. The hull would need to be sturdy and watertight, but also lightweight enough to fly. If a package was attached to be dropped from the boat issues would also arise with the efficiency of it being propelled through the water. The concept also runs into the same issue as concept 1 in terms of accuracy for package delivery. Design for the quadcopter would also need to be much more robust, and in turn expensive, to accommodate the extra weight of the boat frame in flight.

Concept 4: Winch delivery system

Concept 4 is similar to concept 1 but with a different delivery system added. By using a winch to deliver the package underwater the dropping of the package can be a much more controlled process. Choosing an appropriate powered winch is important as its lift to weight ratio is important for flight. It will also have an increased buoyancy system to ensure the quadcopter stays above water even if the package is being lifted back to the surface. The ability to retrieve the package or pull something back up to the quadcopter is an added bonus to this design. Like concept 1, it is not required for the entire structure to be watertight and submerged which simplifies design and manufacture. The concept also would require few servos which makes the concept easily adaptable to other controllers.

3.3.3 Final Summary

WINNER: Concept 2

The main advantage of concept 2 over the concepts is the ability to place a package with precision underwater (unlike concepts 1,3,4). It would be unimpeded by overhangs and is able to reposition itself while underwater. It was able to take off from the water (unlike concept 3). It was able to stay in the air for the desired amount of time (unlike concept 3). The concept is also able to be constructed from readily available parts like PVC tubing which allows pieces to be modified and replaced easily. It also allows the design to be scaled easily for the lifting capacity needs.

3.4 Proposed Performance Measures for the Design

Quadcopter-Sub Performance Goals

- Quadcopter can be airborne for at least 10 minutes
- Quadcopter can fly at an altitude of 30m
- Quadcopter can be fully submerged at 3m
- Quadcopter can carry a 2kg payload
- Quadcopter can resurface and take off from water
- Quadcopter can float on surface of water
- Quadcopter is capable of releasing payload underwater

3.5 Design Constraints

Functional:

The original design problem suggested the drone should not only be able to land on water but to submerge. There are many constraints in terms of weight and density so that it can stay afloat and then sink when filling up the ballast system. Also, materials selection was limited by their ability to interact with water. The added weight of the ballast system, as well as the operation of the water pumps also increased the power requirements, reducing the flight range.

Safety:

Drone operation can be hazardous if not exercised with caution. The quadcopter uses brushless motors with propellers spinning at high speed. They can potentially injure the operator of anyone nearby it. Also, the drone needs to be built solidly to ensure the torque being generated by the motors does not cause the arms to break apart. Another safety concern is the operation of electrical circuits. Thorough inspection of the connections needs to be carried out before powering everything up.

Quality:

Even though building the drone did not require a lot of machining or tight tolerancing, the overall quality of the sealing needed to be substantial. If water were to enter the main body, all the electrical components would be damaged beyond repair. Also, choosing reliable components such as motors is key to a successful project.

Manufacturing:

The team was limited to modify existing components, designed to be waterproof, such as PVC electrical boxes and piping. The analysis suggested it was the best material choice due to its strength, impermeability and light weight. The availability of tools like mills and drill presses, considerably simplified the manufacturing tasks.

Timing:

The drone project was a semester long project. This was a challenging factor that forced the team to simplify the complexity of the design and also prevented from being able to test thoroughly the initial prototype and adjust the design accordingly. Clearly, there were many prior steps to manufacturing that reduced the time span to actually work on building the drone.

Economic:

The allocated budget was $400. This limiting factor required the team to be frugal in choosing parts, nevertheless budgeting needed to be adjusted upwards due to the inability to find reliable electric components, mainly the motors. The ones originally purchased had factory defects which pushed the timetable backwards.

Ergonomic:

Since a drone needs to be able to fly, the size is important. Building a very heavy and large drone can potentially prevent it from flying. Also, it loses the ability to move with agility in the air. Moreover, it should be portable and fairly easy to carry around.

Ecological:

There were no major constraints in this aspect. Proper waste disposal, especially after soldering and machining is required to prevent pollution. After the life cycle of the batteries is over, those need to be disposed in an adequate way.

Life cycle:

One of the requirements of the project was that the drone should be reusable. This characteristic made the project challenging since the team had to test the waterproofing of the final prototype. Everything needed to be completely finalized before sinking the drone.

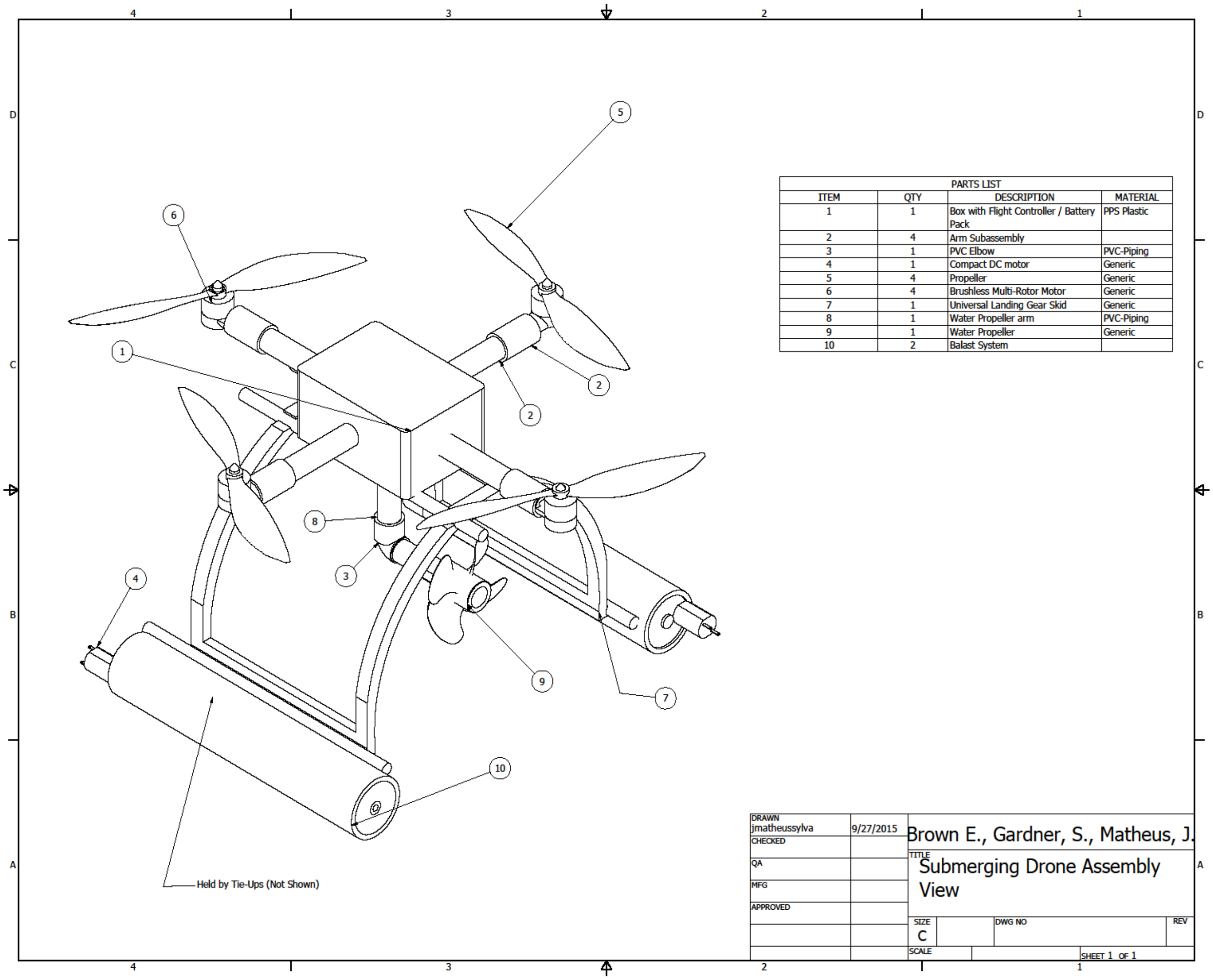
Legal:

There has been a lot of debate revolving drone use and safety / privacy issues. The team consulted the latest FAA (Federal Aviation Authority) regulations to ensure the operation and testing of the drone was performed in compliance with the existing legislation.

4 Embodiment and Fabrication Plan

4.1 Embodiment Drawings

Figure 9: Embodiment Drawing Isometric View



PARTS LIST			
ITEM	QTY	DESCRIPTION	MATERIAL
1	1	Box with Flight Controller / Battery Pack	PPS Plastic
2	4	Arm Subassembly	
3	1	PVC Elbow	PVC-Piping
4	1	Compact DC motor	Generic
5	4	Propeller	Generic
6	4	Brushless Multi-Rotor Motor	Generic
7	1	Universal Landing Gear Skid	Generic
8	1	Water Propeller arm	PVC-Piping
9	1	Water Propeller	Generic
10	2	Balast System	

DRAWN jmatheussylva 9/27/2015
CHECKED
QA
MFG
APPROVED
Brown E., Gardner, S., Matheus, J.
TITLE Submerging Drone Assembly View
SIZE C
DWG NO
REV
SCALE
SHEET 1 OF 1

Figure 10: Embodiment Drawing Top View

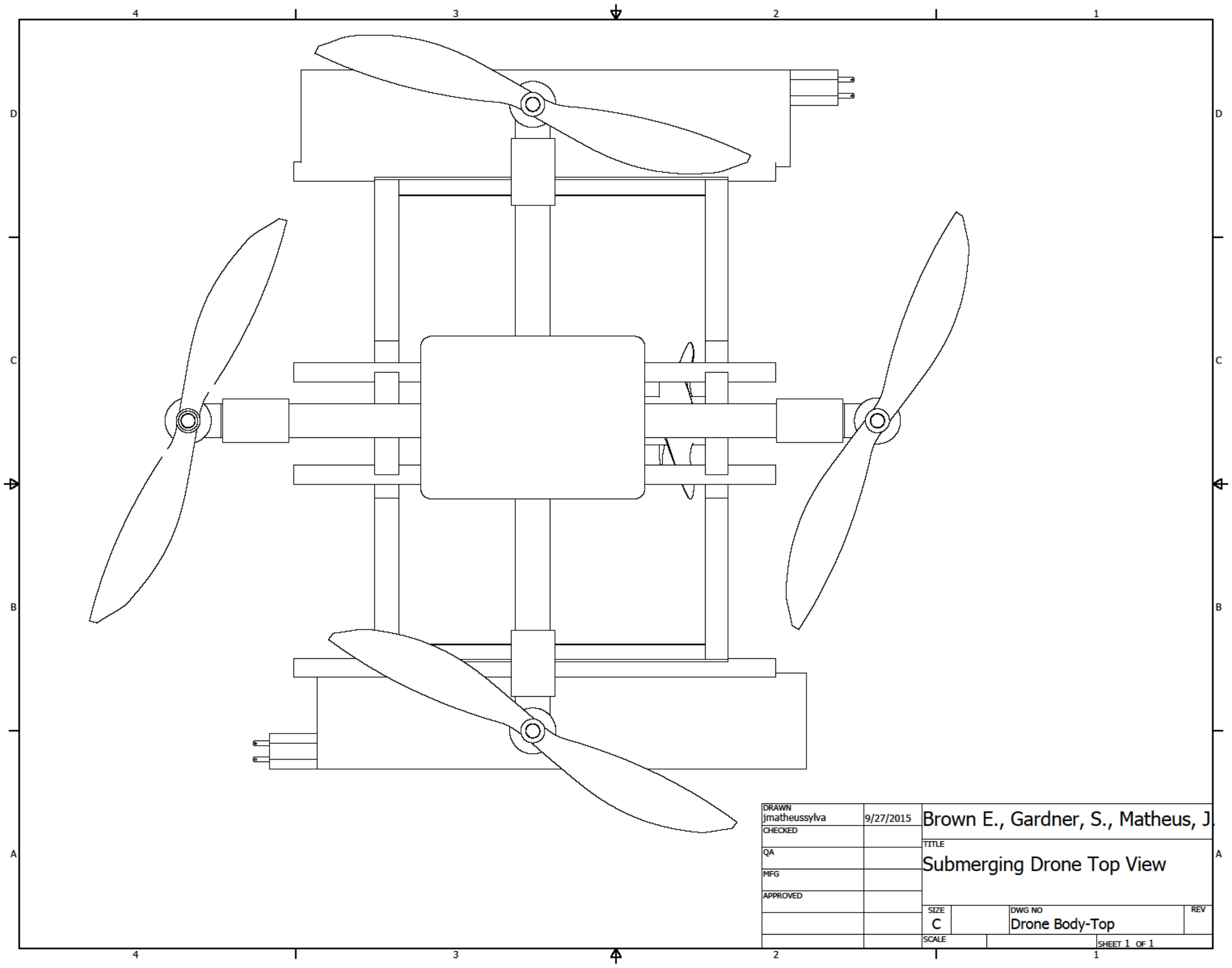
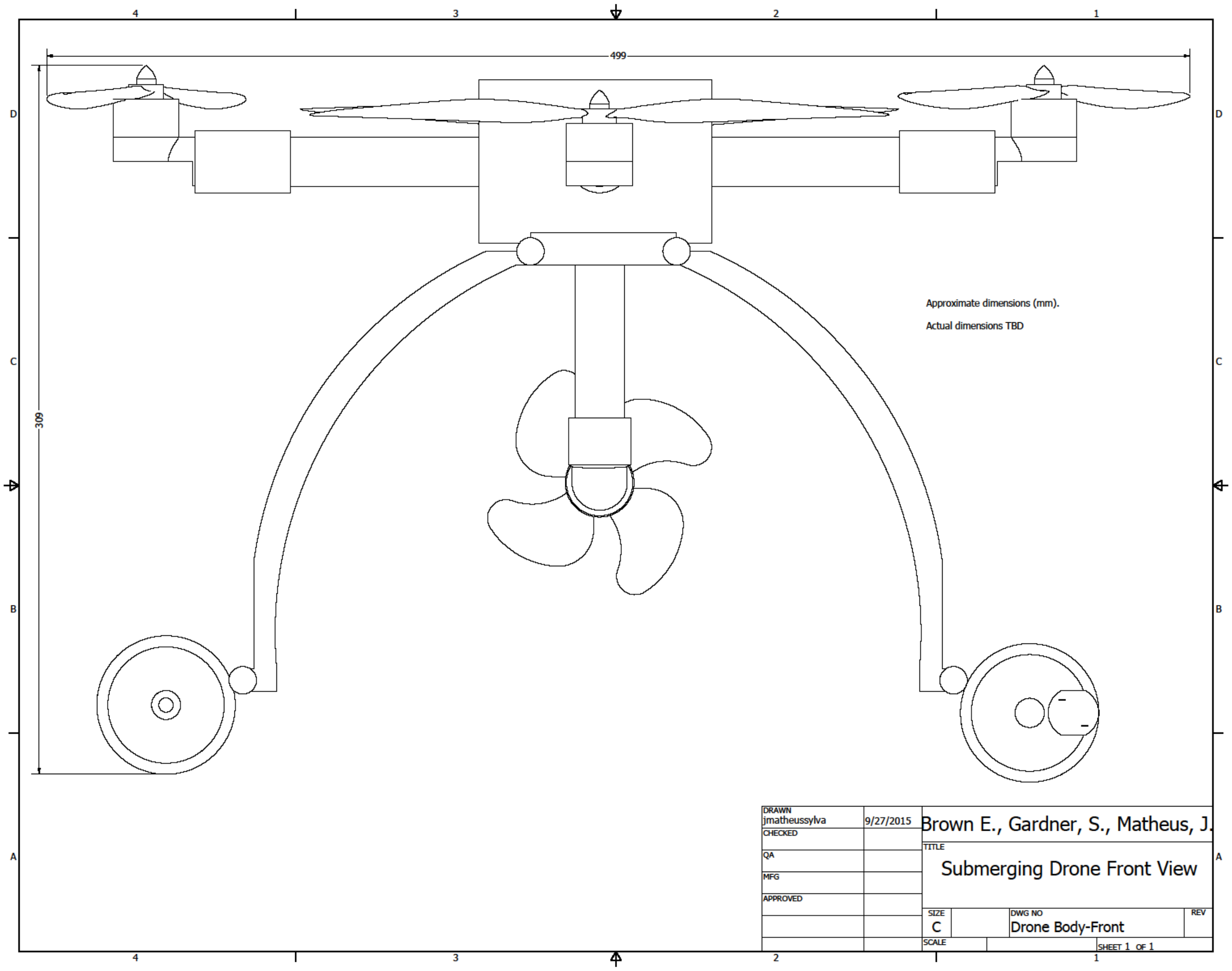


Figure 11: Embodiment Drawing Front View



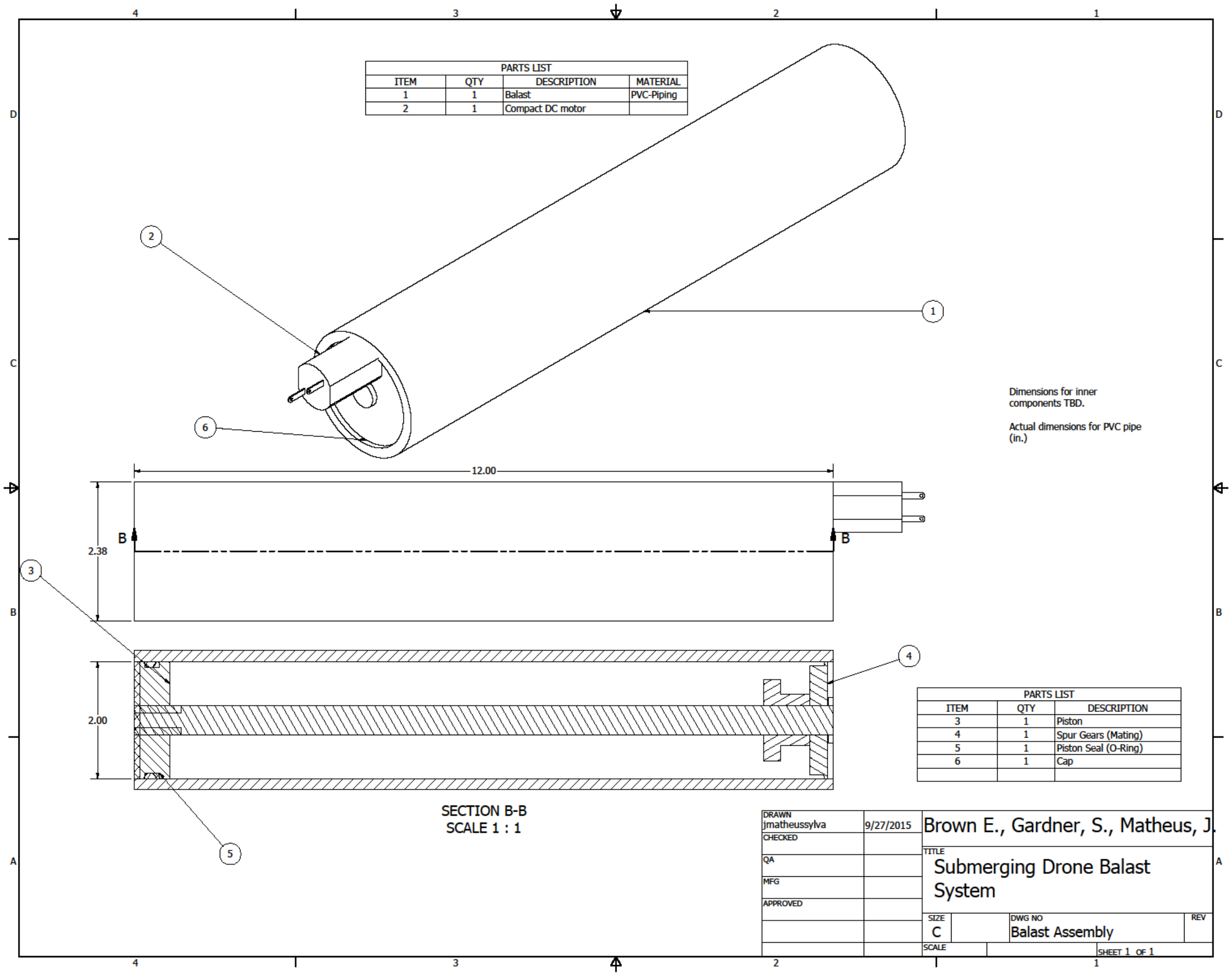
4.2 Parts List

Table 4: Preliminary Parts List

Part	Website	Catalog Numbers	Quantities	Price per Unit	Price
PVC Unthreaded 1/2 Pipe (10 ft)	McMaster-Carr	48925K91	1	4.13	4.13
1/2 PVC Female Unthreaded Couple	McMaster-Carr	4880K71	10	0.2	2
1/2 PVC Female Unthreaded Cross	McMaster-Carr	4880K241	1	1.16	1.16
1/2 PVC Female Unthreaded Elbow	McMaster-Carr	4880K771	1	0.86	0.86
AeroSky Performance Brushless Multi-Rotor Motor	HobbyPartz	05M-21-MC2212-980KV-14P	4	15.95	63.8
Metric Pan Head Philips M3 Machine Screws (20mm Length)	McMaster-Carr	90116A165	1	9.28	9.28
8 oz. PVC Cement	Home Depot	100345577	2	3.32	6.64
Intermatic WP3100C Plastic In-Use Weatherproof Receptacle Cover	Amazon	ASIN: B001PKP4J6	1	7.95	7.95
PVC Unthreaded 2 Pipe (4ft)	McMaster-Carr	49035K28	1	36.94	36.94
Multipurpose O-Rings (OD 2")	McMaster-Carr	9452K119	1	8.42	8.42
GENS ECO 2200mAh 11.1V 20C	HobbyPartz	32P-20C-2200-3S1P-111	2	13.59	27.18
Chemical Resistant PVC (1ft) (2 in Diameter)	McMaster-Carr	8745K26	1	9.15	9.15
Brass Threaded Stock 1/4"-20 (3 ft)	McMaster-Carr	98853A029	1	7.51	7.51
Uncoated Low-Strength Steel Hex Nut	McMaster-Carr	90490A028	1	2.1	2.1
BW FPV Anti Vibration Universal Type Landing Skid Kit Gear	Amazon	ASIN: B00T9H2UW	1	19.58	19.58
Multipurpose Sleeve Bearings	McMaster-Carr	6381K467	1	1.49	1.49
*note: wireless transmitter/receiver yet to be determined				Total Price:	208.19

4.3 Draft Detail Drawings for Manufactured Parts

Figure 12: Detailed Drawing of the Proposed Ballast System



PARTS LIST

ITEM	QTY	DESCRIPTION	MATERIAL
1	1	Balast	PVC-Piping
2	1	Compact DC motor	

PARTS LIST

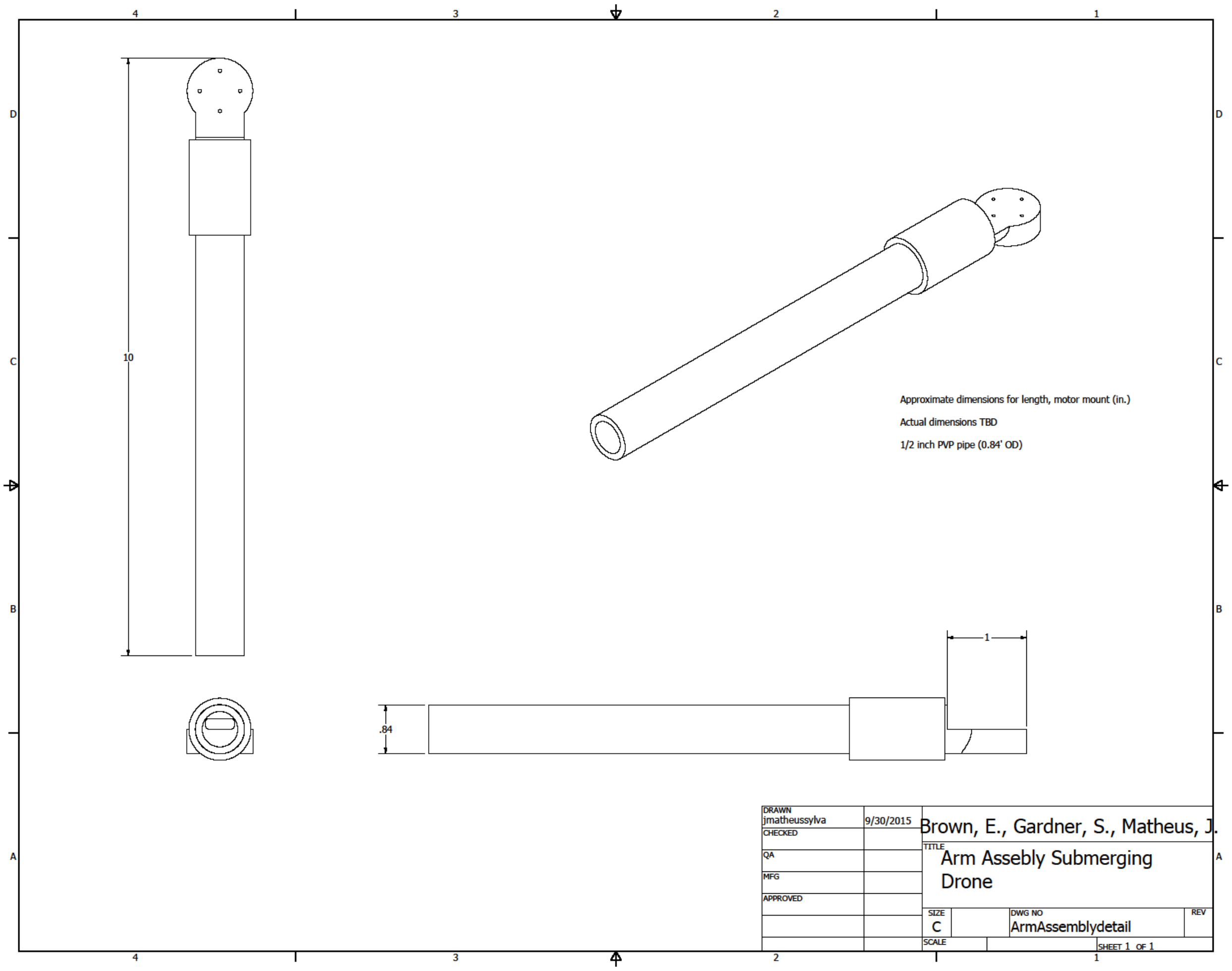
ITEM	QTY	DESCRIPTION
3	1	Piston
4	1	Spur Gears (Mating)
5	1	Piston Seal (O-Ring)
6	1	Cap

Dimensions for inner components TBD.

Actual dimensions for PVC pipe (in.)

DRAWN jmatheussylva	9/27/2015	Brown E., Gardner, S., Matheus, J.
CHECKED		TITLE Submerging Drone Balast System
QA		
MFG		
APPROVED		SIZE C · DWG NO Balast Assembly · REV
		SCALE · SHEET 1 OF 1

Figure 13: Detailed Drawing if the Proposed Motor Mount System



4.4 Design Rationale

The typical quadcopter design uses an open air mount for the electronic systems. Since we need the quad to be submergible we need to add a watertight box to house the electronic systems. We elected to purchase an outdoor surge box to use as the watertight box for the quadcopter frame. This was chosen because the volume of the box is large enough to hold the flight controller and the mounts for the arms while remaining lightweight enough for flight. The other main advantage to using this box is that it is designed to house electronics in outdoor environments so it comes with gaskets around the outside of the box, allowing it to be opened closed to make adjustments to the internals of the box while keeping it watertight during flight or submersion.

Part 2: Arms

We have chosen to use ½ in PVC piping for the arms that connect the flight motors and rotors to the watertight electric housing box. This was chosen because the PVC is lightweight, strong, and easily waterproofed by using PVC cement. It is also hollow so the wires can be run through them. The primary design concern for the arms is the buckling force on the PVC tube at the hub connection point. This calculation was done using the equation below:

$$F = \frac{\pi E I}{(KL)^2}$$

The arms will be fixed at the connection point and the force applied at the end of the arm by the motors. Using these boundary conditions, we get values of:

$$K = 2$$

$$I = \frac{\pi}{4}(r_2^4 - r_1^4)$$

$$E = 490ksi$$

$$r_1 = 0.602\ in$$

$$r_2 = 0.840\ in$$

$$L = 8\ in$$

Using these values, we get a buckling force of 5440 lbf, which is significantly higher than the maximum lift force generated from each motor.

Part 3: Propeller

When selecting the appropriate flight propeller, the primary concern is the load that the quadcopter must lift. Our quadcopter will have an AUW (all up weight) of roughly 2.5 kg or 5.5 lbs. To ensure maneuverability and safety for the quadcopter we calculate that it should be able to lift double the AUW. So each propeller/motor combo must be able to produce a lift of ½ the AUW. The most efficient way to do this is to have a longer propeller with a slower spin rate. This requires a small amount of trial and error so we will be trying both a 10-inch and 12-inch propeller with a pitch of 4.5. Using these calculations, we should be able to provide a lift of just over 1.25 kg per motor.

Part 4: Motor

The motor selection is based heavily upon the propeller selection and AUW of the quadcopter. Using the parameters of our quadcopter (2.5 kg AUW, 12 x 3.5 prop) we need a nominal kv of 708 per motor to provide the required 5kg total lift. Matching this figure with the available motors on hobbypartz.com we find that the optimal motor is AeroSky Performance Brushless Multi-Rotor Motor MC2217, 800KV. We can use the ESC to throttle down the motor to optimize efficiency if necessary.

Part 5: Landing skid

The landing skid has several purposes on the quadcopter frame. The primary purpose is to protect the frame from impact on landing. A secondary purpose is to serve as a mount for things like the ballast system and a camera. There are several universal landing skids that are commercially produced that offer all of the features we need and can be purchased very cheaply. For this we have elected to purchase the

Part 6: Ballast system cylinder

The primary function of this is to hold the piston and be able to be filled with water to alter the buoyancy of the frame. We elected to use PVC again, this time the 2” variant, for this function. We selected this because it will have to be custom fit and PVC is cheap, easy to acquire and easy to machine. This will be made by cutting a larger stock of PVC piping down to size.

Part 7: Ballast system piston

The piston is comprised of a piston head and shaft. For the shaft we will be using a threaded brass rod. It must be threaded so that we can control how much water is let into the system by using geared electric motors. The piston cap is fabricated out of a solid PVC rod that can be lathed down to size. We will use 2” rod and machine it down to fit snugly into the cylinder with O-rings.

Part 8: O-rings

The O-rings needed for the piston must fit snugly inside the 2” diameter pipe. We will use 2” OD O-rings with a thickness of 0.07 inches. These can be found on Amazon.com.

Part 9: Ballast Motors

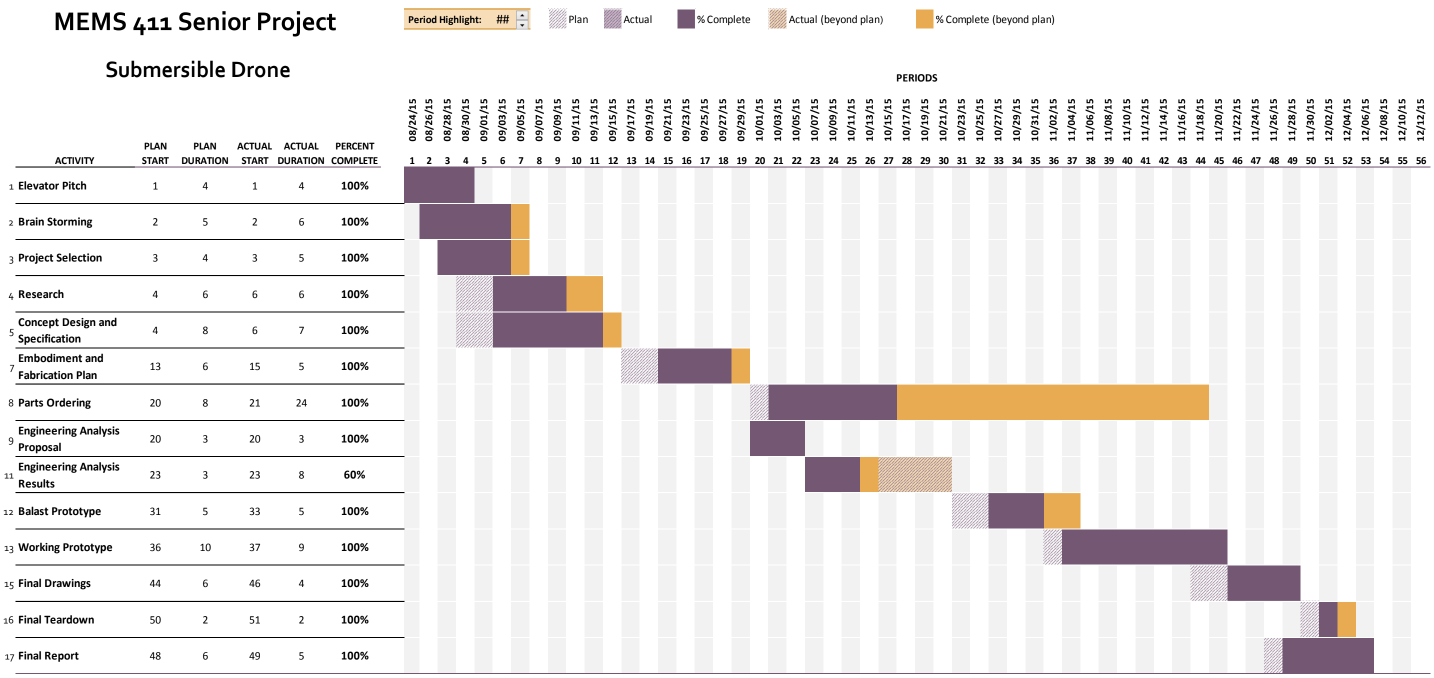
The ballast system motors used will be low voltage DC motors that can turn the spindle to alter the volume of water allowed inside the system. The motors to be used are

Part 10: Cross connector

The arms will be mounted to a cross connector that is located inside the watertight box. This is to provide an added stability to the arms and to ensure they are all mounted to the same center. We will be using a basic PVC connector joint from McMaster Carr that fits the ½” pipe we are using for the arms.

4.5 Gantt chart

Table 5: Gantt Chart depicting outline of the Project Timeline



MEMS 411 Senior Project

Submersible Drone

	ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
1	**Elevator Pitch**	1	4	1	4	**100%**
2	**Brain Storming**	2	5	2	6	**100%**
3	**Project Selection**	3	4	3	5	**100%**
4	**Research**	4	6	6	6	**100%**
5	**Concept Design and Specification**	4	8	6	7	**100%**
7	**Embodiment and Fabrication Plan**	13	6	15	5	**100%**
8	**Parts Ordering**	20	8	21	24	**100%**
9	**Engineering Analysis Proposal**	20	3	20	3	**100%**
11	**Engineering Analysis Results**	23	3	23	8	**60%**
12	**Balast Prototype**	31	5	33	5	**100%**
13	**Working Prototype**	36	10	37	9	**100%**
15	**Final Drawings**	44	6	46	4	**100%**
16	**Final Teardown**	50	2	51	2	**100%**
17	**Final Report**	48	6	49	5	**100%**

5 Engineering analysis

5.1 Engineering analysis proposal

The Submersible Drone was instructed to wait on the analysis proposal. The instructors had concerns able the execution of the ballast system and how it would affect the drone. Engineering Analysis began after the instructors received confirmation the ballast system was working.

5.2 Engineering analysis results

5.2.1 Motivation. Describe why/how the before analysis is the most important thing to study at this time. How does it facilitate carrying the project forward?

The before analysis is crucial to the design process so that it can be determined whether or not the project is worthwhile to pursue in its current form. In the before analysis calculations such as lift required, weight of craft, required motors, and buoyancy need to be performed to understand if it is feasible to create the project in the given amount of time with the given resources. If it is determined that the design can be completed within the constraints, then the project may move forward. If a problem arises that cannot be overcome, then the design must be modified or a different concept should be selected.

5.2.2 Summary statement of analysis done. Summarize, with some type of readable graphic, the engineering analysis done and the relevant engineering equations

The analysis done for this project included: weight of the craft, required power and motors to achieve flight, buoyancy of the craft, deflection on the arms of the craft, and pump rates of the ballast system.

5.2.3 Methodology. How, exactly, did you get the analysis done? Was any experimentation required? Did you have to build any type of test rig? Was computation used?

All of the analysis was done using Microsoft Excel. The relevant equations were found either through textbooks from previous classes or independent research. Obtaining the mass was done while creating our initial parts list. Each part was listed with its specs in an excel spreadsheet and the total mass was found by taking the sum of the parts. In order to determine the amount of thrust required for each motor the total mass of the system was divided by two. This included the lift factor of 2. In order to calculate the buoyancy of the system the following equation was used:

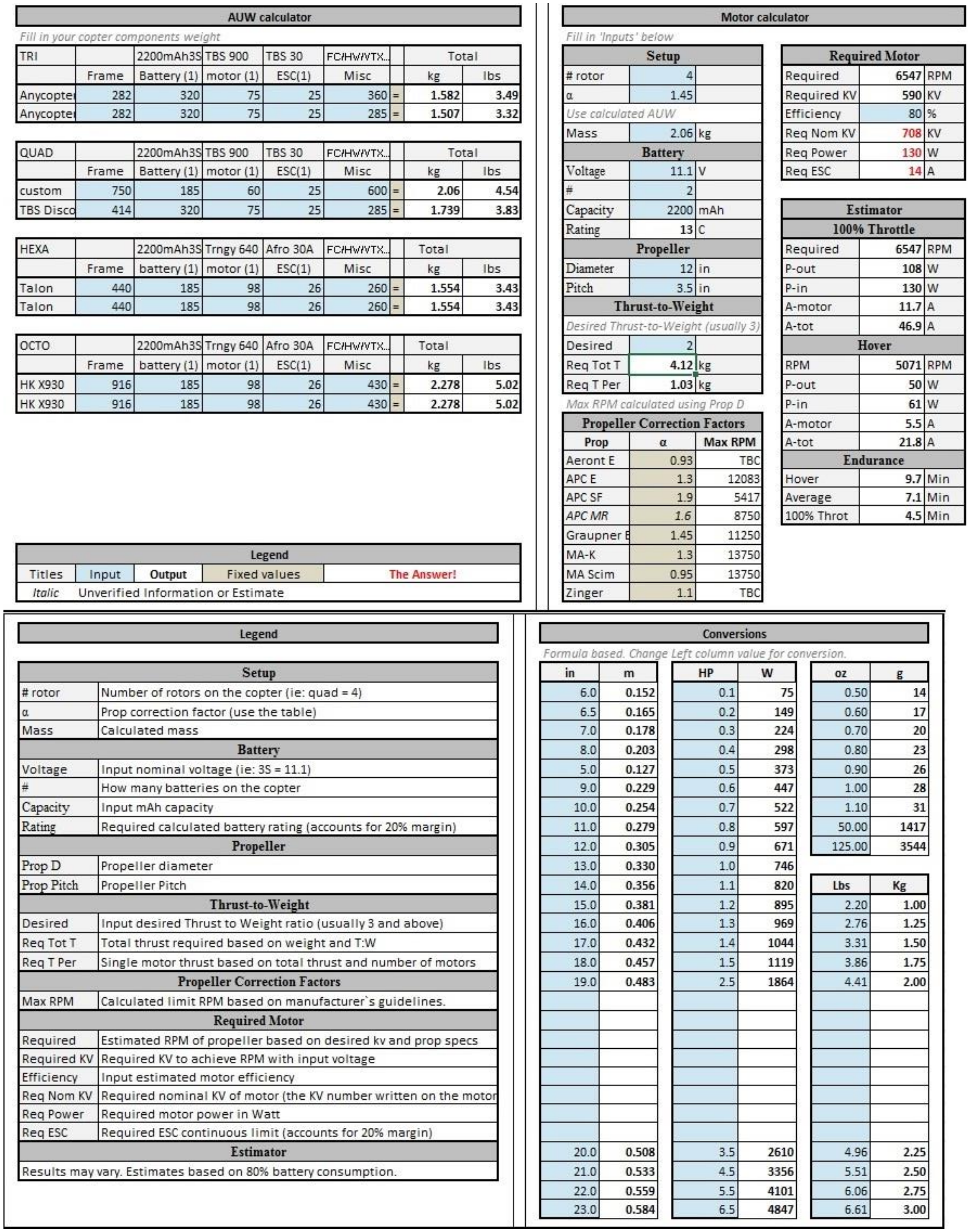
$$F_b = V_s \rho_w g$$

The buoyancy of each part of the system was calculated and summed. From these calculations the ballast was designed so that the craft could sink and rise in the water. The analysis of the arms was done using structural analysis equations for a tube with the material properties of PVC.

5.2.4 Results. What are the results of your analysis study? Do the results make sense?

It was determined that using the materials chosen in the initial design made a drone that had a weight of 8 pounds and that proper motors and propellers could be purchased within the means of the budget. The buoyancy of the craft without ballast was -1.5lbs, so the ballasts were construct to have a natural buoyancy of +3lbs, and could be adjusted down to -2 lbs. The arms were found to a yield stress 5000 times higher than the expected maximum load, which is well above the required amount. It was also determined that the deflection on the arms was insignificant and would not have an effect on the propellers.

Table 6: Excel Spreadsheet to determine the power of the motors required for the drone weight.



AUW calculator

Fill in your copter components weight

TRI		2200mAh3S	TBS 900	TBS 30	FC/HW/VTX…		Total	
	Frame	Battery (1)	motor (1)	ESC(1)	Misc		kg	lbs
Anycopter	282	320	75	25	360	=	1.582	3.49
Anycopter	282	320	75	25	285	=	1.507	3.32

QUAD		2200mAh3S	TBS 900	TBS 30	FC/HW/VTX…		Total	
	Frame	Battery (1)	motor (1)	ESC(1)	Misc		kg	lbs
custom	750	185	60	25	600	=	2.06	4.54
TBS Disco	414	320	75	25	285	=	1.739	3.83

HEXA		2200mAh3S	Trngy 640	Afro 30A	FC/HW/VTX…		Total	
	Frame	battery (1)	motor (1)	ESC(1)	Misc		kg	lbs
Talon	440	185	98	26	260	=	1.554	3.43
Talon	440	185	98	26	260	=	1.554	3.43

OCTO		2200mAh3S	Trngy 640	Afro 30A	FC/HW/VTX…		Total	
	Frame	battery (1)	motor (1)	ESC(1)	Misc		kg	lbs
HK X930	916	185	98	26	430	=	2.278	5.02
HK X930	916	185	98	26	430	=	2.278	5.02

Legend				
Titles	Input	**Output**	Fixed values	The Answer!
Italic	Unverified Information or Estimate			

Motor calculator

Fill in 'Inputs' below

Setup		
# rotor	4	
α	1.45	
Use calculated AUW		
Mass	2.06	kg
Battery		
Voltage	11.1	V
#	2	
Capacity	2200	mAh
Rating	13	C
Propeller		
Diameter	12	in
Pitch	3.5	in
Thrust-to-Weight		
Desired Thrust-to-Weight (usually 3)		
Desired	2	
Req Tot T	4.12	kg
Req T Per	1.03	kg

Max RPM calculated using Prop D

Propeller Correction Factors		
Prop	**α**	**Max RPM**
Aeront E	0.93	TBC
APC E	1.3	12083
APC SF	1.9	5417
APC MR	*1.6*	8750
Graupner E	1.45	11250
MA-K	1.3	13750
MA Scim	0.95	13750
Zinger	1.1	TBC

Required Motor		
Required	6547	RPM
Required KV	590	KV
Efficiency	80	%
Req Nom KV	708	KV
Req Power	130	W
Req ESC	14	A

Estimator		
100% Throttle		
Required	6547	RPM
P-out	108	W
P-in	130	W
A-motor	11.7	A
A-tot	46.9	A
Hover		
RPM	5071	RPM
P-out	50	W
P-in	61	W
A-motor	5.5	A
A-tot	21.8	A
Endurance		
Hover	9.7	Min
Average	7.1	Min
100% Throt	4.5	Min

Legend

Setup	
# rotor	Number of rotors on the copter (ie: quad = 4)
α	Prop correction factor (use the table)
Mass	Calculated mass
Battery	
Voltage	Input nominal voltage (ie: 3S = 11.1)
#	How many batteries on the copter
Capacity	Input mAh capacity
Rating	Required calculated battery rating (accounts for 20% margin)
Propeller	
Prop D	Propeller diameter
Prop Pitch	Propeller Pitch
Thrust-to-Weight	
Desired	Input desired Thrust to Weight ratio (usually 3 and above)
Req Tot T	Total thrust required based on weight and T:W
Req T Per	Single motor thrust based on total thrust and number of motors
Propeller Correction Factors	
Max RPM	Calculated limit RPM based on manufacturer`s guidelines.
Required Motor	
Required	Estimated RPM of propeller based on desired kv and prop specs
Required KV	Required KV to achieve RPM with input voltage
Efficiency	Input estimated motor efficiency
Req Nom KV	Required nominal KV of motor (the KV number written on the motor
Req Power	Required motor power in Watt
Req ESC	Required ESC continuous limit (accounts for 20% margin)
Estimator	
Results may vary. Estimates based on 80% battery consumption.	

Conversions

Formula based. Change Left column value for conversion.

in	m	HP	W
6.0	0.152	0.1	75
6.5	0.165	0.2	149
7.0	0.178	0.3	224
8.0	0.203	0.4	298
5.0	0.127	0.5	373
9.0	0.229	0.6	447
10.0	0.254	0.7	522
11.0	0.279	0.8	597
12.0	0.305	0.9	671
13.0	0.330	1.0	746
14.0	0.356	1.1	820
15.0	0.381	1.2	895
16.0	0.406	1.3	969
17.0	0.432	1.4	1044
18.0	0.457	1.5	1119
19.0	0.483	2.5	1864
20.0	0.508	3.5	2610
21.0	0.533	4.5	3356
22.0	0.559	5.5	4101
23.0	0.584	6.5	4847

oz	g
0.50	14
0.60	17
0.70	20
0.80	23
0.90	26
1.00	28
1.10	31
50.00	1417
125.00	3544

Lbs	Kg
2.20	1.00
2.76	1.25
3.31	1.50
3.86	1.75
4.41	2.00
4.96	2.25
5.51	2.50
6.06	2.75
6.61	3.00

5.2.5 Significance. How will the results influence the final prototype? What dimensions and material choices will be affected? This should be shown with some type of revised embodiment drawing. Ideally, you would show a "before/after" analysis pair of embodiment drawings.

The only design modification that had to be made after the analysis were the dimensions of the ballast. However, the original design did not have official dimensions for these parts because we knew that they would depend heavily on the analysis. Another significant result from the analysis was the motor selection. It was found that we would need at least 2 pounds of thrust from each motor to equal the weight of the craft. Generally, a factor of 2 is applied to the required thrust to ensure maneuverability, so motors were selected to have 4 pounds of thrust each.

5.2.6 Summary of code and standards and their influence. Similarly, summarize the relevant codes and standards identified and how they influence revision of the design.

Drone Codes and Standards

- https://www.faa.gov/uas/faq/
- https://www.faa.gov/uas/regulations_policies/
- http://www.howtogeek.com/213159/what-you-need-to-know-before-flying-a-drone/

5.3 Risk Assessment

5.3.1 Risk Identification

The project presented several challenges that had some risk associated with it. Risk does not only involve safety concerns but how to troubleshoot different issues, from parts sourcing to reassessing the design and concept chosen to solve the customer's' unmet needs. Some of the main risks involved in our project had to deal with the inability to fully model and predict the response of our concept prior to construction and machining. Moreover, having worked on a tight budget, there was a risk associated to faulty parts that may cause the prototype to fail, even if the concept was a solid one. Parts sourcing also had some risks tied to it, since we were also working with checkpoints and deadlines, and obtaining the right parts in a timely manner was something we had to handle. As mentioned throughout this report, one of the main risks had to do with the fact that we were not able to fully test our prototype in time to troubleshoot and reassess since it had to be completely sealed before testing underwater. If water were to get in contact with the electronic components, all the parts would be damaged beyond repair. Therefore, we had to deal with the risk of sealing and cementing all the components permanently before testing submergibility and waterproofing. There were some risks associated as well with the overall weight of the prototype. Engineering analysis showed the electric motors would provide enough lift to take off a structure that would be twice as heavy as we predicted the final prototype would weigh, but there was uncertainty with the ballast's ability to sink the drone without becoming too heavy for it to take off afterwards. Additional risks had to do with choosing the right parts. Motors, ESC (Electronic Speed Controllers), propellers and flight controllers / receivers had to work in unison. Acquiring a mix and match of parts could potentially prevent our drone from working properly. We understood it had to be done up to a certain extent due to budget constraints and the inability to find parts on the market that were not ready-to-fly full kits.

5.3.2 Risk Analysis

In every major project issues are going to show up. They can be related to anything from safety to manufacturing and build quality. The way we analyzed and assessed risk was to develop scenarios in the first place to make sure we had flushed out all major concerns before starting the parts ordering and building process. We scrutinized each concept and saw what major issues we could run into. Analysis also ruled out different ideas due to complexity of manufacturing, number of parts and cost. Along the way, we had to make minor changes to tackle issues that had to do mainly with parts' sourcing. We also had to look into choosing the right tools, materials and machining techniques to ensure we were proceeding safely, with accuracy and obtaining the expected results.

We did encounter some issues that we identified earlier as sources of risk. Assessing the actual impact on our project was an important part of troubleshooting. Waterproofing the drone's body required us to analyze the best methods to seal. We chose PVC as the main material and used PVC cement to create a seal similar to a weld. We also looked at the wiring and its properties to see whether it could be exposed or not.

We also had to analyze the effects on the timing of the arrival of different parts. We required the main drone parts such as the flight controller to arrive first so we could have that calibrated and assembled and then verify our calculations were not flawed in terms of the payload. In general, most of our risk analysis had to occur simultaneously with the building process since there were things we could not predict.

5.3.3 Risk Prioritization

All risk associated with the safety of the team members during machining, assembling and operation was always our first priority. Budget and timing became another big priority. We had issues with faulty parts that required us to change the scheduling and to request allocation of more resources to move forward. Moreover, changes to our prototype due to unexpected behavior or response required a very thorough assessment of the situation and team collaboration to sort out these issues. As expected, risk prioritization was a team decision.

6 Working prototype

6.1 At least two digital photographs showing the prototype

Figure 14: Front view of Final Prototype

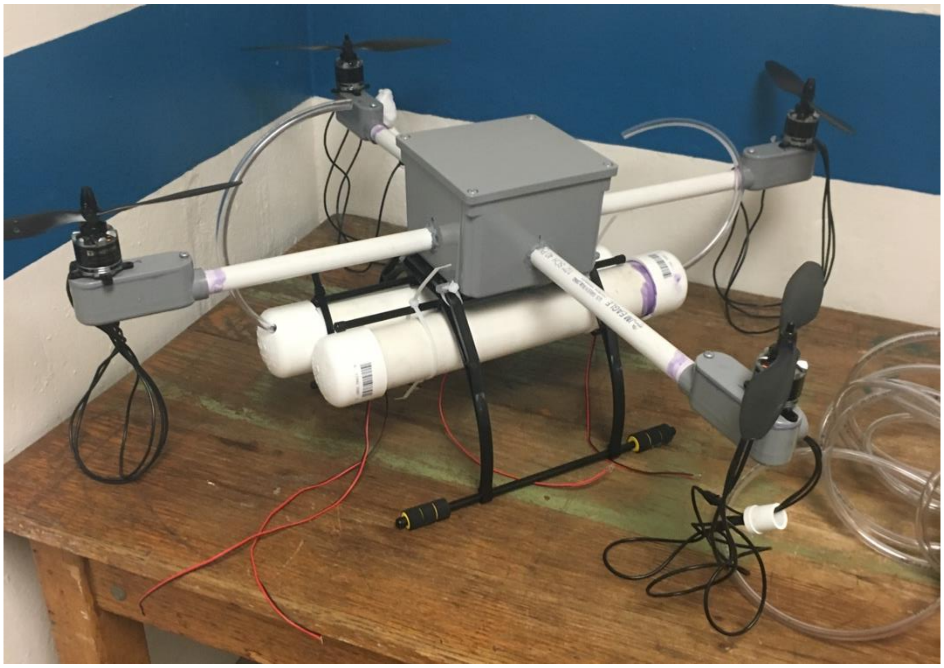
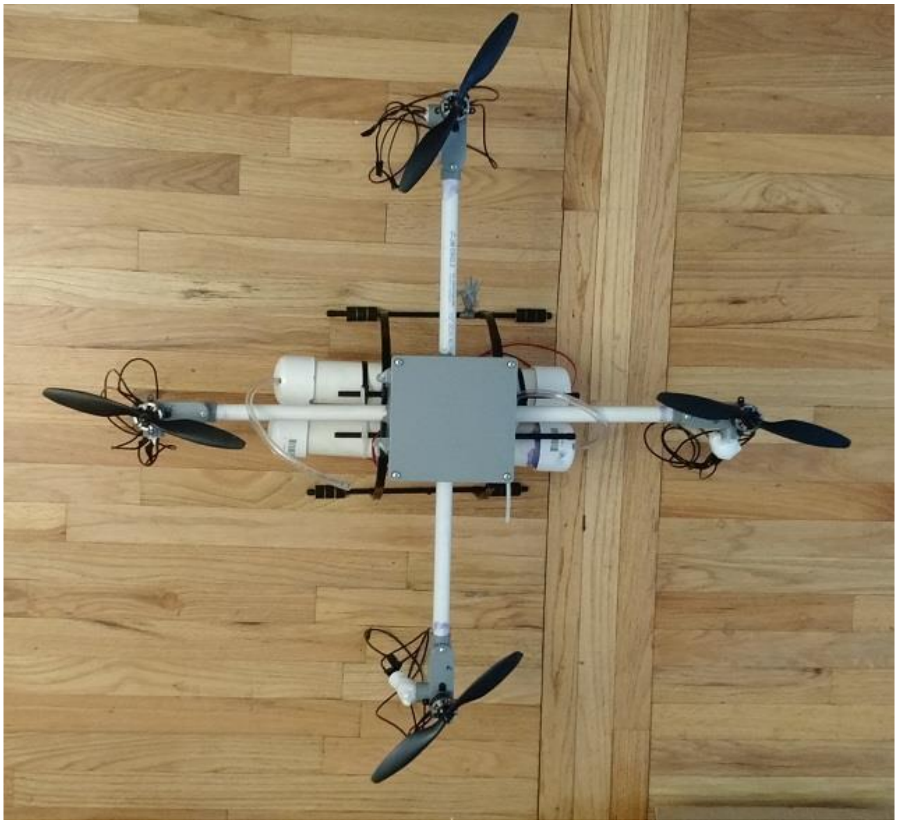


Figure 15: Top view of Final Prototype



6.2 A short video clip that shows the final prototype performing

First Video – Flying Drone

20151201_153031.mp4

Figure 16: Screenshot of the above video.

Video 2 – Sinking Ballast

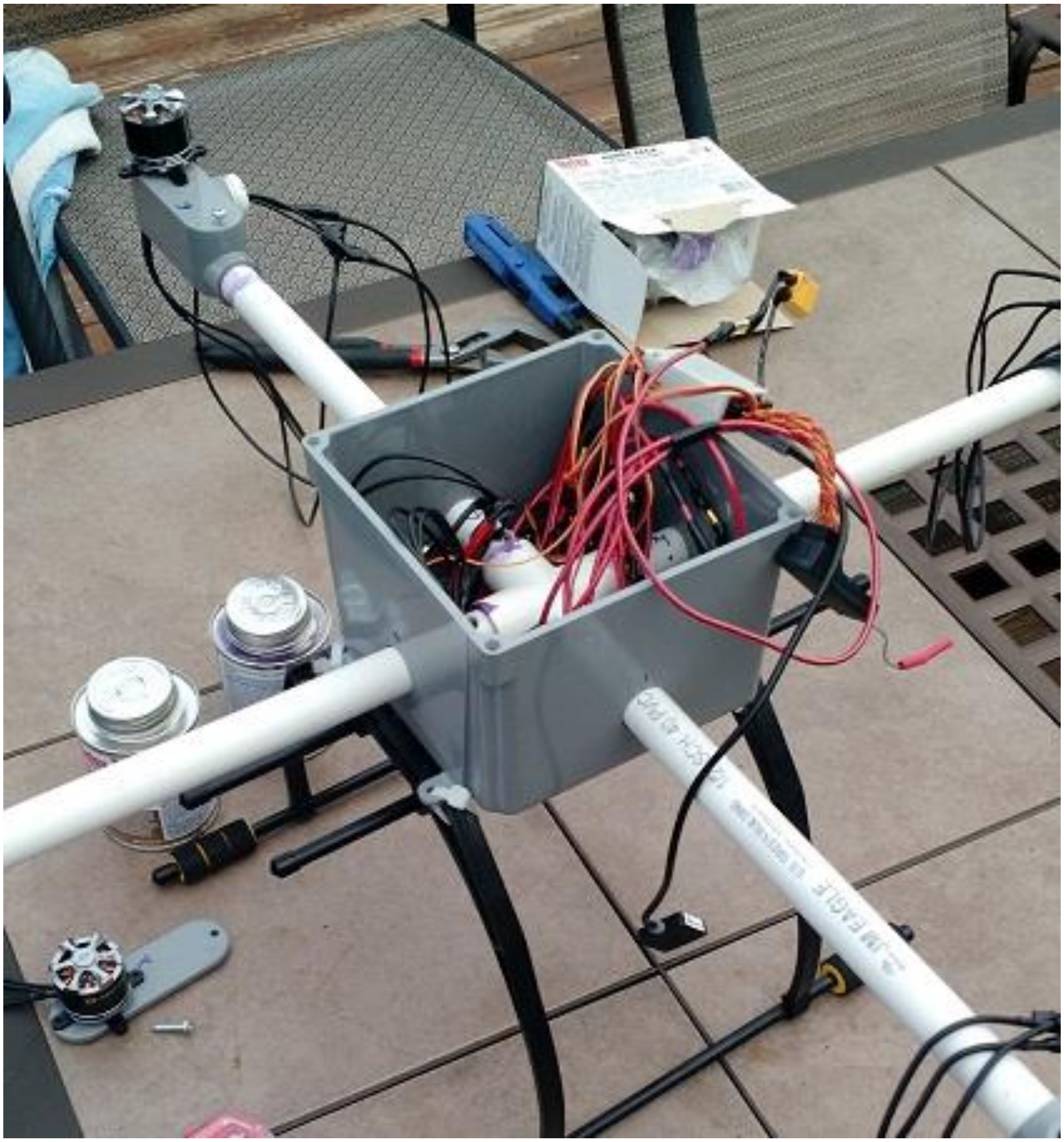
Video 3 – Rising Ballast

6.3 At least four (4) additional digital photographs and their explanations

Figure 17: Motor Mount

PVC junctions served as a flat surface for the motors to be mounted to while also allowing accessibility to the wires inside the arm before sealing the drone. In the image above, the junction is being connected to the arm permanently.

Figure 18: Open Junction Box

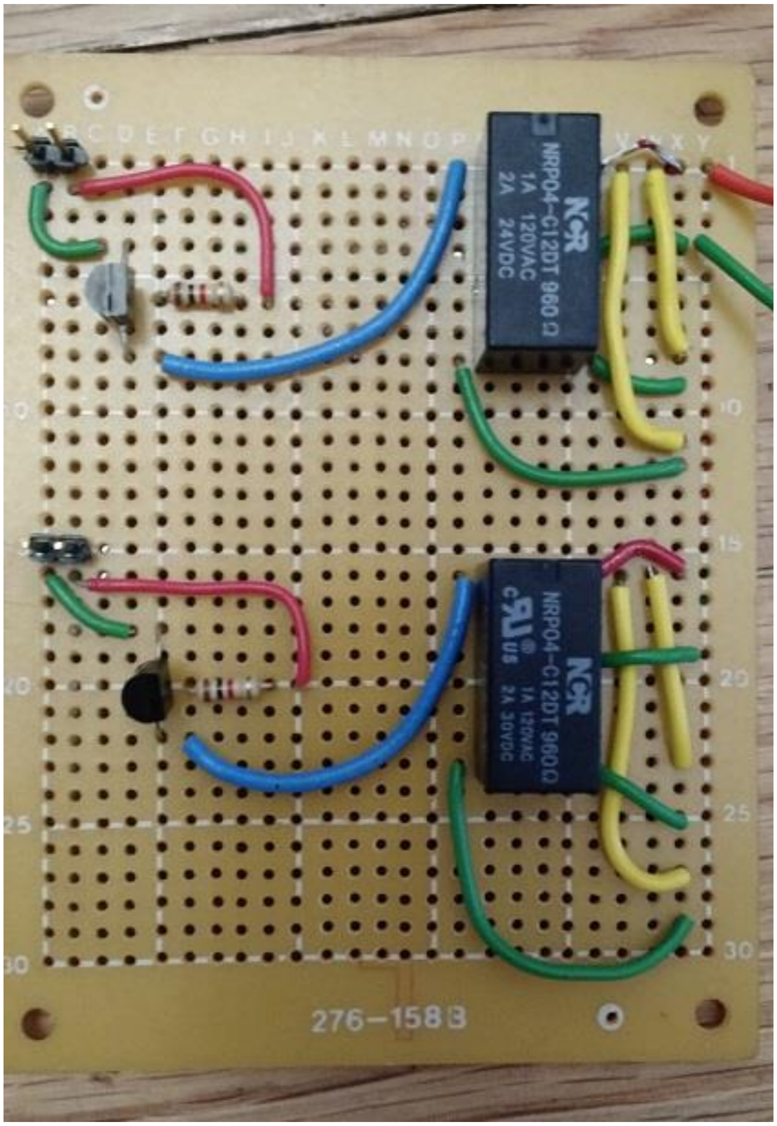


PVC junction box served as the water tight container for all electronic component. In the image above, the junction box is open and the wiring harness can be seen. The wiring harness connections all the electronics that need power to the batteries.

Figure 19: Up close of mounted motor with propeller

Brushless motors are a requirement for a submersible drone. The brushless motors are not to be run while underwater but must be able to be run after being submerged. The motors themselves can't be waterproofed because have to be able to reduce generated heat. In the image above, the slots on the top and bottom each motor – showing the exposed coils – allow the motor to breathe.

Figure 20: Completed Relay Circuit for the Ballast System.



In the image above, the completed relay circuit is show. The relays allow the water pumps to be activated by the radio.

7 Design documentation

7.1 Final Drawings and Documentation

7.1.1 A set of engineering drawings that includes all CAD model files and all drawings derived from CAD models. *Include units on all CAD drawings.* See Appendix C for the CAD models

All Engineering drawings are located in Appendix C.

7.1.2 Sourcing instructions

Table 7: Sourcing Instructions part 1

Purchased Parts	Source	Supplier Part Number	Unit price	Quantity	Total price	Part Description
Magicfly Water Pump	Amazon	DC30A-1230	$10.99	4	$43.96	Pump water in and out
EMAX ESC	HobbyPartz	66P-105-Simon-Series-30A	$12.95	4	$51.80	Transfer power to motors.
T-Motor Brushless Motor	Amazon	MT2814 KV770	$61.90	4	$247.60	Spin propellors
2 Pack Li-Polymer Battery Pack	Amazon	Floureon 3S 11.1V 2200mAh 25 C	$27.99	1	$27.99	Powers electronics
Anti Vibration Universal Landing Skid	Amazon	BW FPV for F450 or F550	$19.58	1	$19.58	Landing surface
Dji Naza-M Flight Controller	Amazon	Lite	$75.00	1	$75.00	Controlls the drone
3Pairs CW CCW Plasitc Propellors	Amazon	12 x 4.5R 1045	$9.66	1	$9.66	Creates Lift
Cheerwing Nylon CW CCW Propellors	Amazon	12 x 4.5R 1045	$8.97	1	$8.97	
FlySky Digital Proportion Transmitter and Receiver	HobbyPartz	FS-T6 2.4ghz 6 Channel	$54.95	1	$54.95	Handheld drone controls
Velleman Assorted Transistor	Micro Center	459263	$27.99	1	$27.99	Protects the circuit
NTE Elect Hook Up Wire 300V	Micro Center	85902	$4.25	1	$4.25	Connects electronics
NTE Elect Relay 2Amp 12VDC	Micro Center	860130	$3.99	3	$11.97	Acts as a swtich
NTE Elect Relay 1Amp 12VDC	Micro Center	8377658	$3.49	1	$3.49	
				Total:	$587.21	

Table 8: Sourcing Instructions part 2

Scrounged Parts	Part Advice	Quantity	Part Description	Approximate Price
6" x 4" x 4" Junction Box	Can be found in most hardware stores.	1	Holds electronics	$12.00
2" Unthreaded PVC pipe	Can be found in most hardware stores.	24"	Acts as ballast	$5.00
1/2" Unthreaded PVC pipe	Can be found in most hardware stores.	48"	Acts as drone arms	$3.00
1/2" Unthreaded PVC Cross	Can be found in most hardware stores.	1	Connects drone arms	$1.00
1/2" PVC Type LL Conduit Body	Can be found in most hardware stores.	4	Surface for mounting motors	$16.00
2" PVC End Cap	Can be found in most hardware stores.	4	Holds water in ballasts	$8.00
1/4" IN (3/8" OD) Tubing	Can be found in most hardware stores.	Depends	Allows air in ballasts	$5.00
PVC Cement	Can be found in most hardware stores.	8oz or more	Permanently connects PVC	$8.00
Waterproof Epoxy	Can be found in most hardware stores.	2oz or more	Waterproofing	$5.00
			Approximate Total Price	$63.00

7.2 Final Presentation

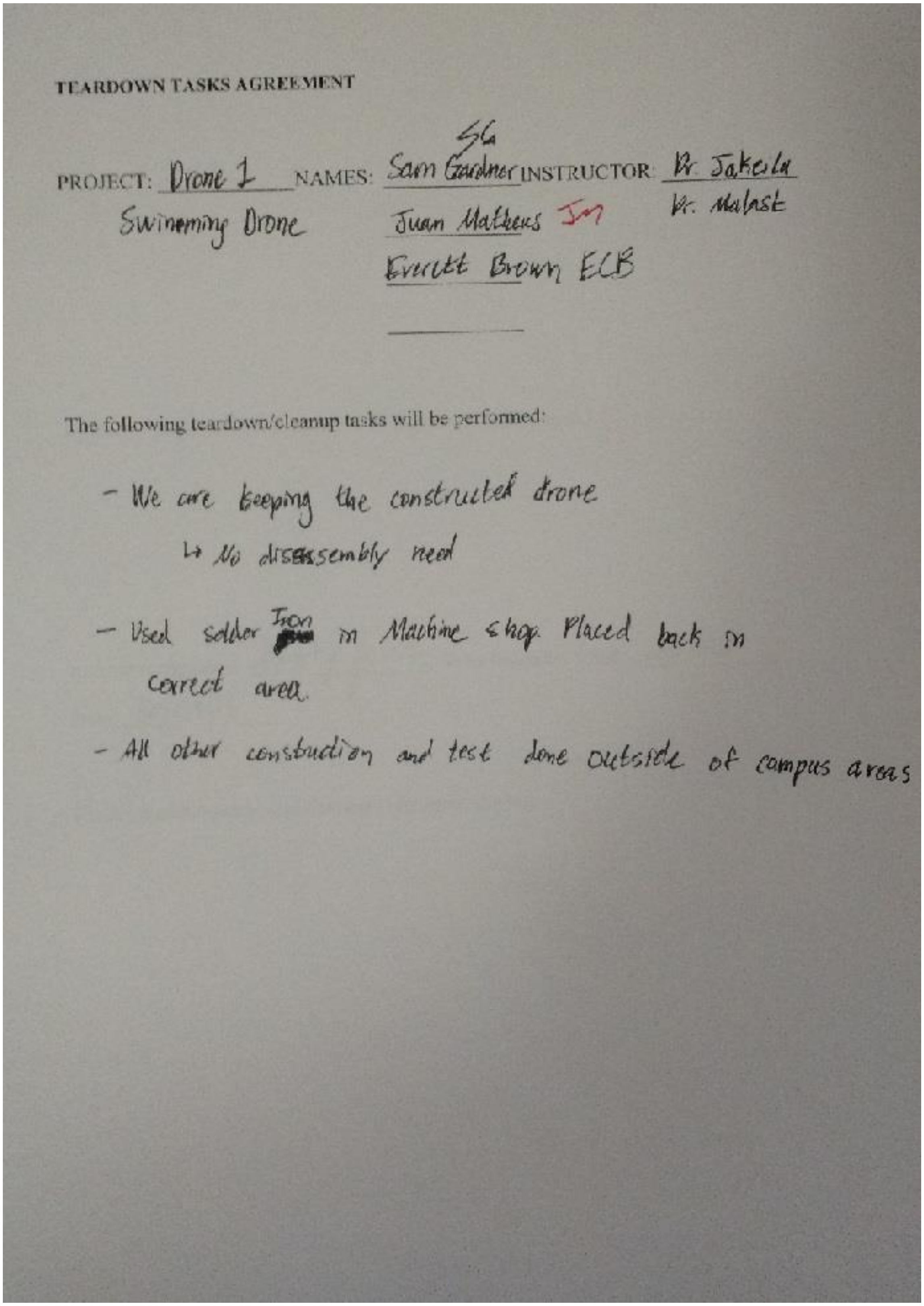
7.2.1 A link to a video clip version of 1

SENIOR DESIGN: DRONE 1

Sam Gardner, Juan Matheus, Everett Brown

7.3 Teardown

Figure 21: Completed Teardown form 1 of 2



TEARDOWN TASKS AGREEMENT

PROJECT: Drone 1
Swimming Drone

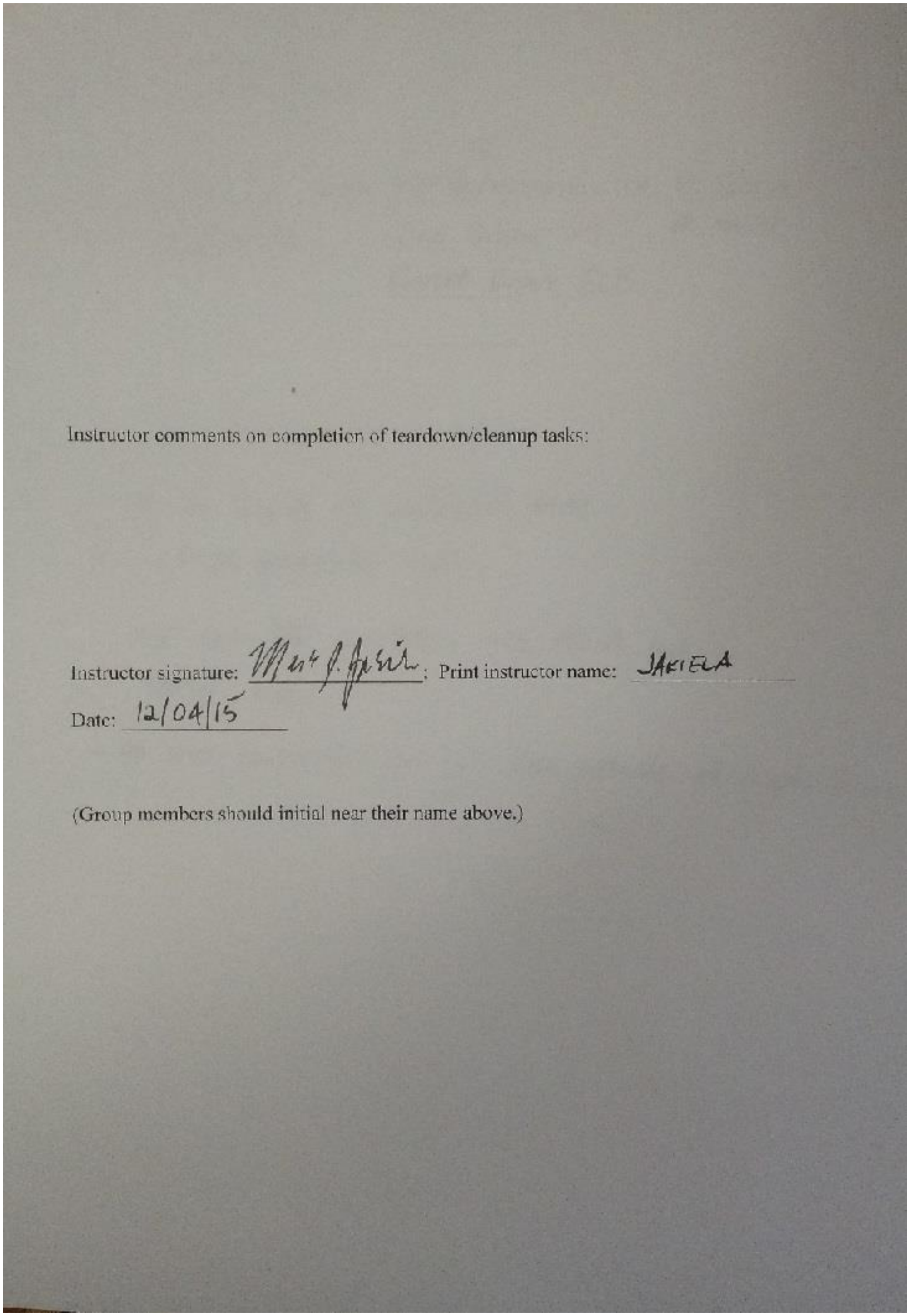
NAMES:
Sam Gardner SG
Juan Mathews JM
Everett Brown ECB

INSTRUCTOR: Dr. Jakeila
Dr. Malast

The following teardown/cleanup tasks will be performed:

- We are keeping the constructed drone
  - ↳ No disassembly need
- Used solder Iron in Machine shop. Placed back in correct area.
- All other construction and test done outside of campus areas

Figure 22: Completed Teardown form 2 of 2



Instructor comments on completion of teardown/cleanup tasks:

Instructor signature: ; Print instructor name: JAKIELA

Date: 12/04/15

(Group members should initial near their name above.)

8 Discussion

8.1 Using the final prototype produced to obtain values for metrics, evaluate the quantified needs equations for the design. How well were the needs met? Discuss the result.

A few of the design needs were met while some proved to be too ambitious or were taken off the last when the design because of its low importance. The submersible drone achieved it flight range, it was reusable, and was able to achieve lift necessary for flight on land and water. However, the flight time was reduced by the total weight of the drone, it was not able to lift an additional 5 lbs. with the motors used, and it is not easy to repair due to all the necessary waterproofing. The camera need was removed.

8.2 Discuss any significant parts sourcing issues? Did it make sense to scrounge parts? Did any vendor have an unreasonably long part delivery time? What would be your recommendations for future projects?

Obtaining the right parts was a crucial part of the project. The team experienced some issues not only with the vendors but with the parts themselves. Buying through the internet is a very convenient way to obtain all the required components from different sources without having to utilize time to go out and search for the right ones, which may or may not be available within reasonable distance from home. We had issues regarding vendors shipping the wrong items. For instance, our ESCs (Electronic Speed Controllers) were supposed to arrive as a package of 4 but we only received one item. A refund was processed but it delayed the assembly of the components. Also, brushless motors came in defective and needed to be replaced. These were fairly cheap and that tied in directly with their quality. Delivery times were good across the board of different vendors. It was helpful to have faculty provide a list of ‘trusted suppliers’, based on previous experience to try to avoid suppliers that are not careful at shipping their orders on time. The recommendation would be to look into improving the budget for each team based on the complexity of the project, especially if a lot of electronic components are involved. Quality and reliability of cheap electronics can compromise a project with a potentially successful concept.

8.3 Discuss the overall experience:

8.3.1 Was the project more of less difficult than you had expected?

Overall, the team underestimated the complexity of waterproofing components and the overall construction of the ballast system. Some redesigning was required to simplify the concept and reduce the number of parts, which is desirable anyways. Also, it was significantly challenging to be able to test the prototype. The drone had to be practically completed before testing. There were some components that needed to be permanently cemented and after that no changes could have been made. Waterproofing also required sealing that had to be final before sinking the drone. Those elements were considered only minor concerns at the beginning of the project.

8.3.2 Does your final project result align with the project description?

The final project is overall satisfactory. It addressed the main unmet needs supplied by the end user and it required design and manufacturing that drew from many engineering disciplines in order to come up with a viable solution to the design problem. It can always be improved, like any prototype, but overall is an innovative add-on to a drone that could find many uses in the future.

8.3.3 Did your team function well as a group?

The team was not dysfunctional in any way. Each person was responsible enough to make sure everyone kept up to date with deadlines and make progress towards completing the project. Communication was effective and we were able to sort out most of the issues we've encountered along the way.

8.3.4 Were your team member's skills complementary?

All groups members worked well together when present at a meeting and during construction and testing. However, all teammates were reluctant to a single person taking a leadership role for the entire project. A leader emerged for each step throughout the semester depending on the type of work. For example, one group member was more familiar with the construction of drones, he would take the lead of understanding the necessary electronics for the drone and their setup while others took care of repetitive construction or assignment logistics.

8.3.5 Did your team share the workload equally?

The submersible drone project was a collection of one man tasks. Therefore, all three group members couldn't all work together on a single step. Understanding unexpected issues may arise, the team came together and volunteered their time to a specific part for each task. Scheduling conflicts were common but when a member was unable to coordinate with the group or participate in a task, he would volunteer to take a larger portion of the next task.

8.3.6 Was any needed skill missing from the group?

The primary skill that was needed by our group that was absent was knowledge of designing circuits. When confronted with the issue of creating a relay circuit to be used with the ballast system the team was lacking. The team was very grateful to have the assistance of the TA Ethan Glassman to help with the design and creation of the circuit.

8.3.7 Did you have to consult with your customer during the process, or did you work to the original design brief?

The customer was not consulted for a change in design during the process.

8.3.8 Did the design brief (as provided by the customer) seem to change during the process?

The design brief did change as needs of low importance - a stated by the customer - reduced the feasibility of the final prototype.

8.3.9 Has the project enhanced your design skills?

The project has greatly enhanced the design skills of the team. The biggest issue the design team encountered was learning to navigate the issues of budget and suppliers. Our team also learned a lot about manufacturing processes and designing parts around the limitations of the manufacturing capabilities. The team has also learned the difficulties in approaching the mechanical-electrical interface.

8.3.10 Would you now feel more comfortable accepting a design project assignment at a job?

Overall the group has a much better understanding of what is expected in a design project and would feel more comfortable accepting such a project. With the experience of this class we have a much better idea of how to create an appropriate timeline and how to design parts for cost minimization and ease of manufacturability.

8.3.11 Are there projects that you would attempt now that you would not attempt before?

Yes.

9 Appendix A - Parts List

Table 9: Updated Parts list

Part	Website	Quantities	Price per Unit	Price
Magicfly DC30A-1230 12V DC 2 Phase	Amazon	4	$10.99	$43.96
Neewar 30A Brushless ESC Set with 3A/5V BEC for RC Quadcopter Multi-copter APM2 (4 PCS)	Amazon	1	$29.95	$29.95
2 Packs Floureon 3S 11.1V 2200mAh 25C Li-Polymer Battery Pack with XT60 Connector Plug	Amazon	1	$27.99	$27.99
BW FPV Anti Vibration Universal Type Landing Skid Kit Gear for F450 F550 Quadcopter	Amazon	1	$19.58	$19.58
Dji Naza-M Lite Main Controller Only	Amazon	1	$75.00	$75.00
3Pairs 12 x 4.5R 1245R Two Blades CW CCW Black Plastic Propellers	Amazon	1	$9.66	$9.66
Cheerwing Nylon 12x4.5" 1045 CW CCW Propeller For Multicopter Quadcopter Black 4 Pair	Amazon	1	$8.98	$8.98
T-Motor Brushless Multi-Rotor Motor MT2814 KV770	Amazon	4	$61.90	$247.60
FlySky FS-T6 2.4ghz Digital Proportional 6 Channel Transmitter and Receiver Model	HobbyPartz	1	$54.95	$54.95
			Total:	$517.67

10 Appendix B - Bill of Materials

Table 9: Updated Parts list

Part	Website	Quantities	Price per Unit	Price
Magicfly DC30A-1230 12V DC 2 Phase	Amazon	4	$10.99	$43.96
Neewar 30A Brushless ESC Set with 3A/5V BEC for RC Quadcopter Multi-copter APM2 (4 PCS)	Amazon	1	$29.95	$29.95
2 Packs Floureon 3S 11.1V 2200mAh 25C Li-Polymer Battery Pack with XT60 Connector Plug	Amazon	1	$27.99	$27.99
BW FPV Anti Vibration Universal Type Landing Skid Kit Gear for F450 F550 Quadcopter	Amazon	1	$19.58	$19.58
Dji Naza-M Lite Main Controller Only	Amazon	1	$75.00	$75.00
3Pairs 12 x 4.5R 1245R Two Blades CW CCW Black Plastic Propellers	Amazon	1	$9.66	$9.66
Cheerwing Nylon 12x4.5" 1045 CW CCW Propeller For Multicopter Quadcopter Black 4 Pair	Amazon	1	$8.98	$8.98
T-Motor Brushless Multi-Rotor Motor MT2814 KV770	Amazon	4	$61.90	$247.60
FlySky FS-T6 2.4ghz Digital Proportional 6 Channel Transmitter and Receiver Model	HobbyPartz	1	$54.95	$54.95
			Total:	$517.67

11 Appendix C - CAD Models

Figure 23: Ballast End Cap Design

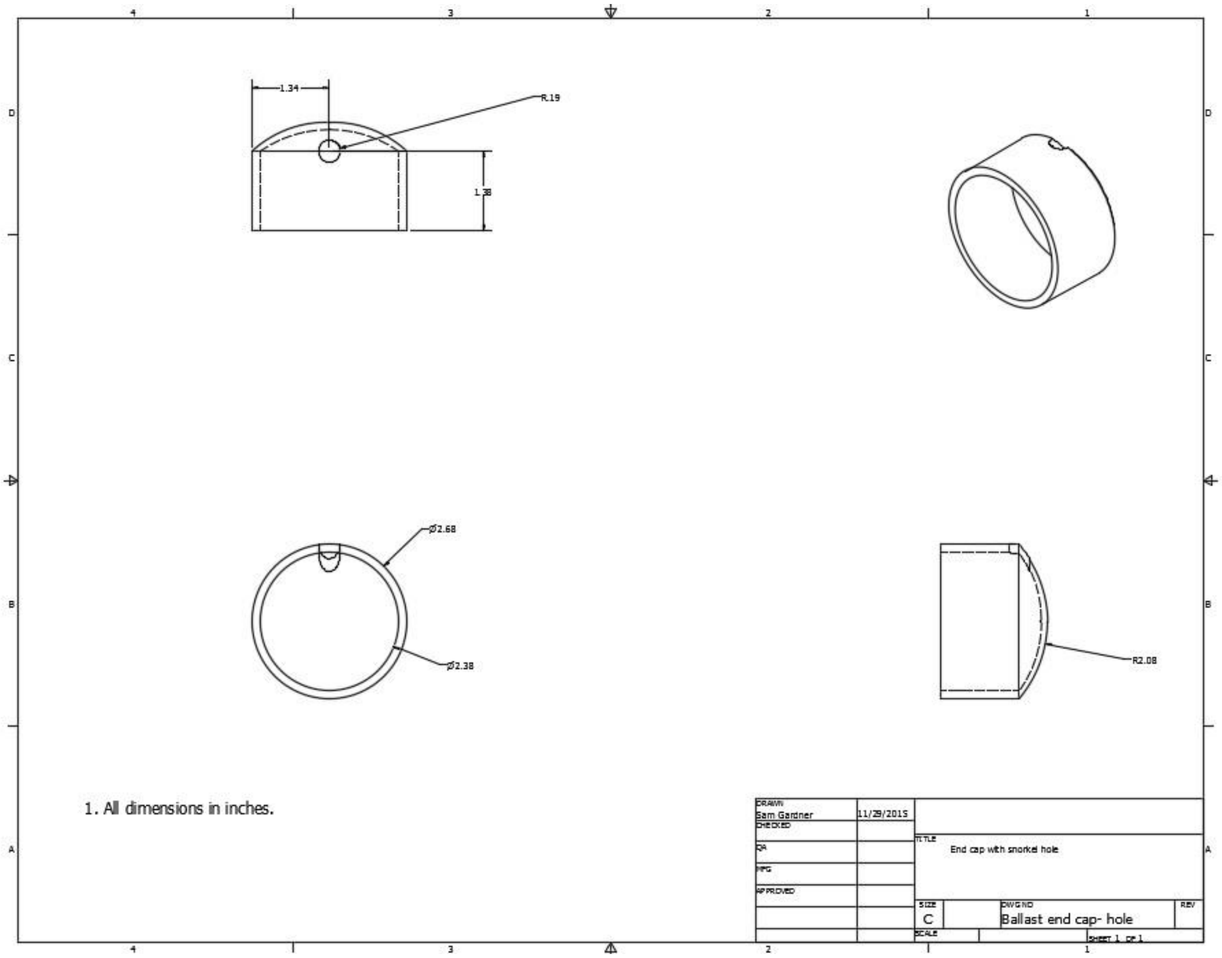
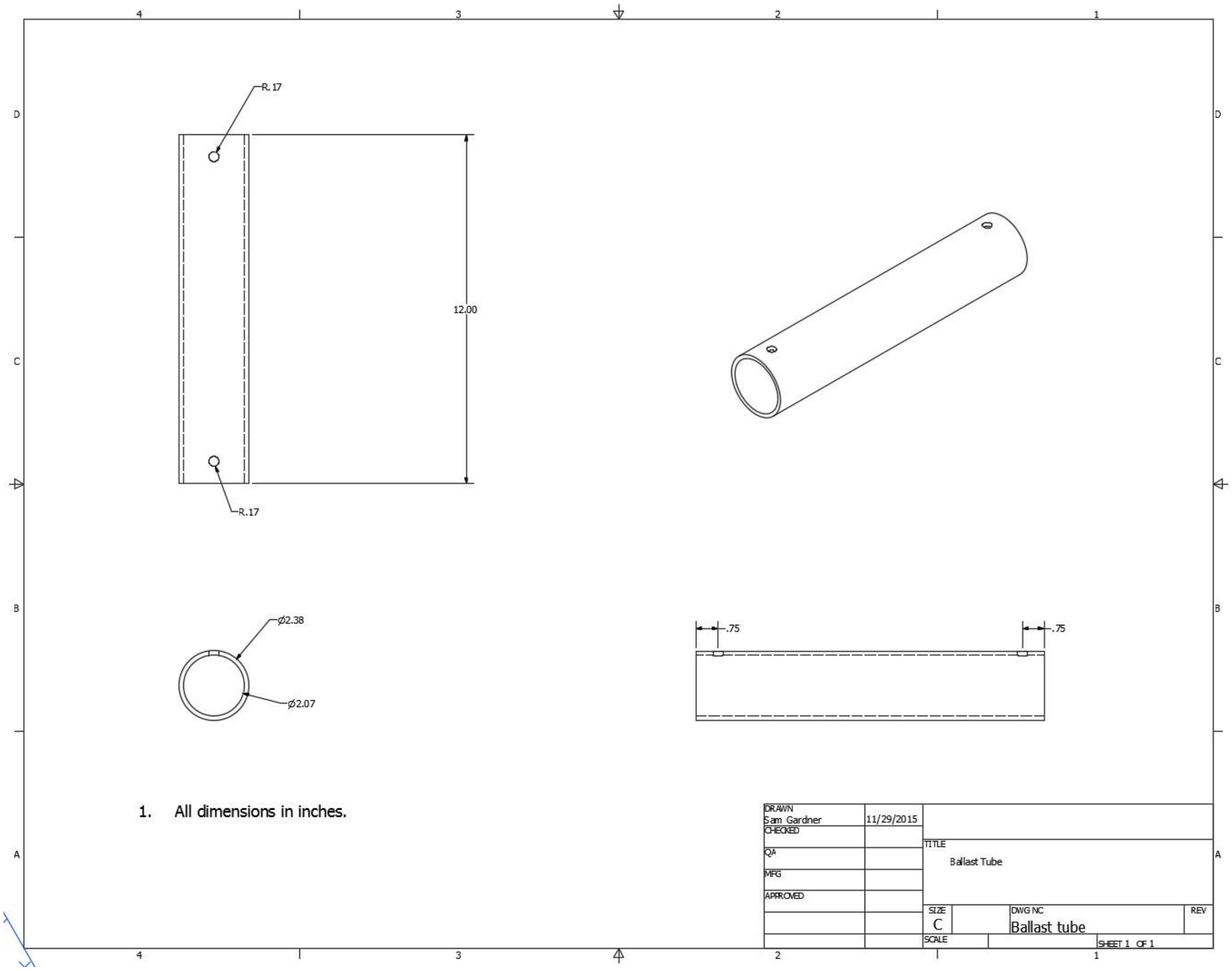


Figure 23: Ballast Design



12 Annotated Bibliography (limited to 150 words per entry)

"Unmanned Aircraft Systems (Uas) Regulations." *Federal Aviation Administration*. United States Government, 21 Oct. 2015. Web. 7 Dec. 2015. <https://www.faa.gov/uas/regulations_policies/>.

> FAA website was only used to understand the codes and standards of Unmanned Aircraft Systems. Additionally, faa.gov provided frequently asked questions by businesses and/or other hobbyists.

Short, Alec. "Wavecopter: A Waterproof Quadcopter." *Make: Projects*. N.p., n.d. Web. 7 Dec. 2015. <http://makezine.com/projects/wavecopter-a-waterproof-quadcopter/>.

> The above article from Make magazine shows the process of creating a water resistant quadcopter. Although the article topic isn't as thorough as the submersible drone, the article will provide waterproofing techniques and avoid various pitfalls as the project progresses.