Cook Engineering Design Center

Final Design Review

Submitted in partial fulfillment of the requirements for

ENGS 90: Engineering Design Methodology and Project Completion

AIMGRO: Aerial-Insertion Micro Ground Robot

March 3, 2017

Sponsored by

Physical Sciences, Inc

Project Team #1

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Executive Summary

The ability to survey areas of interest before deploying military personnel is a valuable and often lifesaving advantage in tactical operations. Physical Sciences Inc.'s (PSI) InstantEye is an unmanned aerial vehicle (UAV) serving exactly this purpose. However, the UAV lacks the ability to get certain surveillance views from the ground. This gap in the technology hinders the detection of potentially lethal obstacles such as concealed improvised explosive devices (IED). The project goal is to address this gap by developing a ground robot that can be dropped from the InstantEye UAV to augment the existing system's viewpoints. To be effective the robot must be light enough to be carried by the InstantEye, survive falls from a range of heights, and communicate with a control station on the ground via XBee radios.

The AIMGRO team has developed two complete prototypes; an initial prototype, the Mk 1, and a final prototype, Mk 2. The Mk2 successfully survives the impact of a thirty foot fall, retains adequate functionality, and minimizes weight. This is made possible by PORON® XRD® 09500-65 foam wheels that are large enough to compress and absorb impact forces without allowing the chassis to contact the collision surface. The Mk 2 chassis is divided into an inner electronics housing and an outer carbon sheath. The two end plates in the chassis absorb force from the drive axle and transfer it directly to the carbon shell, preventing the majority of impact forces from affecting the electronics. The final MK 2 prototype (Mk 2-3), as presented at the end of ENGS 89/90, weighs 577 grams. Including a dropping mechanism provided by PSI, the entire AIMGRO system weighs 674 grams, which is just below the threshold mass of 680 grams.

In accordance with PSI's goals for this project, the group is providing one Mk 1 prototype, three Mk 2 prototypes, documentation for CAD, the manufacturing process, the assembly process, testing results, and suggestions for moving forward. These are recommendations for updated machining processes, light-weight materials, and electronics with a smaller form-factor. To characterize the current prototypes the team has completed approximately 35 drops from various heights and saw success (driving after impact) at heights from 10 to 35 feet. Each AIMGRO vehicle survived multiple drops at 35 feet passing, the threshold of one successful drop per vehicle. The success rate up to 15 feet was 100%, although the rate of success with multiple drops decreased noticeably with height.

The AIMGRO 89/90 prototype is a good starting point for further development to minimize weight, increase survivable fall height, and improve robot terrain accessibility. Decreasing the dimensions of the electronics, which currently dictate the size of the chassis, would reduce the size and mass of the entire system. With this diminished weight and the addition of a drag mechanism, the vehicle would be able to survive greater falls. Finally, experimentation with replaceable and alternative wheels and tails could help optimize the vehicle for different types of terrain. These changes will create a vehicle that not only meets the threshold specifications, as the current prototype does, but makes progress towards the ideal design objectives.

Acronym List

Aerial Insertion Micro Ground Robot	AIMGRO
Computer Numerical Control	CNC
Department of Defense	DoD
Ground Control Station	GCS
InstantEye	IE
Improvised Explosive Device	IED
Mark	Mk
Minimum Viable Product	MVP
Physical Sciences Incorporated	PSI
Proof of Concept	PoC
Serviceable Available Market	SAM
Small Unmanned Aerial System	sUAS
Target Market	TM
Total Available Market	TAM
Unmanned Aerial Vehicle	UAV

Unit List

Robot Volumes	Inches^3
Robot Dimensions	Inches
Distances	Feet
Mass	Grams (g)
Forces	Newtons
Sound Level	Decibels
Time	Seconds & Minutes
Accelerations	Earth Gravity's (g's)

Note: SI units are generally preferred. However, to align with provided specifications for drop heights and dimensions, IPS units are used in specific cases.

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1 Overview

Physical Sciences Inc. Tactical Robotics (PSI) provides cost effective and innovative solutions to improve the operational effectiveness of the Department of Defense, law enforcement, first responders, and commercial customers. Their current product is a small unmanned aerial system (sUAS) known as InstantEye (IE) that provides rapid situational awareness.

However, as an sUAS, it cannot provide a low angle perspective to see under obstacles such as cars or rubble. This surveillance gap prevents many users from evaluating the situation fully. To fill this need for comprehensive surveillance, this project focused on design and development of an aerial insertion micro-ground robot (AIMGRO) that can conduct ground-based operations. To be successful, the proof of concept (PoC) prototype needed to be liftable by the air vehicle, survive a viable deployment fall, and have video capabilities on the ground.

The AIMGRO team has developed two generations of a PoC Prototype. The first electronics-capable and driving PoC Prototype will be referred to as the Mark (Mk) 1 PoC Prototype. This model was designed for a parachute-included system, and thus currently only demonstrates mobility functionality. The Mk 2 PoC Prototype exhibits full functionality as defined by the FDR Threshold Specifications and was used for all dropping tests. The Mk 2 PoC Prototype contains substantial structural improvements to the chassis and is the final deliverable prototype to PSI, though the earlier Mk 1 PoC Prototype will be handed off to demonstrate driving functionality.

Expressly, the deliverables for this project are as follows:

- Four assembled AIMGRO PoC Prototypes (one Mk 1 and three Mk 2)
- Documentation for the manufacture, assembly, and capabilities of the AIMGRO PoC Prototypes

Figure 1: AIMGRO Mk 2 Proof of Concept Prototype

As will be described, the project has produced these deliverables meeting the given specification requirements, multiple ground robots have been created and tested, and the associated documentation is compiled. These deliverables will allow PSI to continue research and product development.

2 Methodology

2.1 Specifications

Several requirement specifications were updated following the Critical Design Review (CDR). This shift redefined the project goal from a set of specifications for the end product to a set of required FDR Threshold Specifications and PSI Product Specifications. The FDR Threshold Specifications represent the specifications that the AIMGRO team worked toward post-CDR while keeping in mind the PSI Product Specifications to guarantee a future path forward for PSI. The details of this shift are described fully in Table 2.1.

Description	PDR Specifications	FDR Threshold Specifications	PSI Product Specifications	Priority
Survivable Fall Height	300 ft	30 ft	300 ft	High
Reusability	1 drop	1 drop	10 drops	High
InstantEye Attachment	Rigid attachment. No dangling components prior to release.	Rigid attachment. No dangling components prior to release.	Rigid attachment. No dangling components prior to release.	High
System Mass	500 g	680 g	226 g	Medium
System Size	150 in^3	150 in^3	45 in^3	Medium
Drive Time	10 min	5 min	> 15 min	Medium
Mobility	Navigate on flat hard ground and packed dirt	Navigate on flat hard ground and packed dirt	Navigate on grass, sand, as well as small obstacles up to 2 inches	Medium
Accuracy of Drop	No requirement	No requirement	Land within a 20 degree cone	Medium
Noise Emission	No requirement	No requirement	65-85 dB	Low
Cost	A manufactured product should cost under $500	Prototype fabrication under $3000	A manufactured product should cost under $500	Low

Table 2.1: Original & Updated Specifications

The most notable changes are the height of drop, system mass, and multi-use intentions. These changes reflect three major alterations in the project objective. The AIMGRO PoC Prototypes must be reusable to serve in repeated demonstrations, rather than being disposable as in the eventual PSI Product. In following with this demonstration use-case, there must be at least three viable prototypes presented to PSI at the end of the course. Finally, PSI has specified that the PoC Prototype must not have a parachute system due to perceived complexity. To accommodate this, the drop height requirement specification was decreased.

The PoC Prototype must be deployable from the IE air vehicle and capable of navigating urban areas of operations. PSI has requested that the PoC Prototype have a mass of under 680 g to improve tactical flight of the IE Generation 4 air vehicle, and the PoC Prototype must be small enough such that it does not impede rotor air flow ($< 150\text{in}^3$). The deployment height and mobility requirement specifications reflect that the typical urban environment has three-story buildings ($\approx$ 30 ft tall) with pavement or hard packed dirt. Given the final PSI Product's likely use in hostile environments, discreteness is paramount to success. New requirement specifications were suggested to quantify discreteness: the impact of the PSI Product must emit less noise than a typical conversation, and the PSI Product must land within a 20° cone of the deployment location.

2.2 Design & Development

The change in requirement specifications led to a notable change in the design and development of the prototype. The removal of the parachute system precluded the feasibility of the current light-weight design. A new, more robust and heavier design was developed to enable the robot to survive the higher impact accelerations. The data collected during wheel testing estimated a 50 g impact on the 30 ft or greater free fall. This leads to a estimated impact force of 248 N transfered into the chassis. This force compares to the estimated impact of 10.6 g and 52 N under the original specifications using the parachute system. See Appendix C for the parachute calculations.

2.2.1 Wheels

The wheels are the only component of the Mk 2 PoC Prototype designed to damp the impact force. A pendulum system was designed to simulate impact forces at increasingly higher heights by increasing the amount of mass in the pendulum bob. The wheels are mounted to a cylindrical center piece that contains a PCB Piezotronics accelerometer, which measures the acceleration of impact as felt by this "chassis."

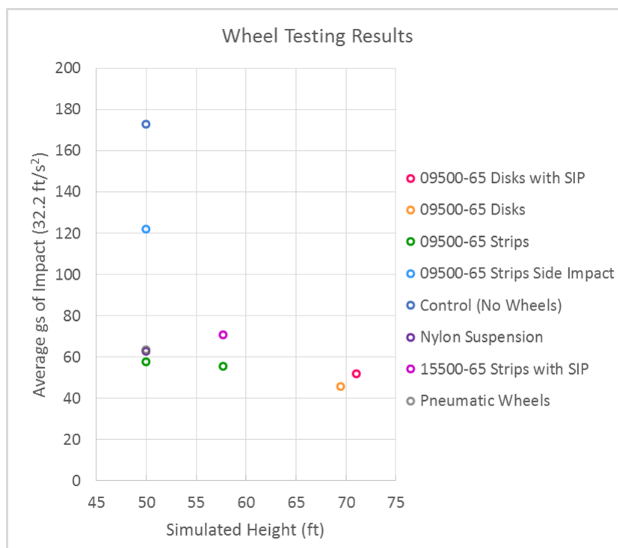


Figure 2: Wheel Accelerometer Testing

Testing prior to the PDR clearly demonstrated the force-absorbing capabilities of PORON® XRD® Extreme Impact Protection, a urethane foam material produced by the Rogers Corporation. The majority of tests conducted after the PDR involved wheels that incorporated different densities of PORON® XRD® and compared their damping capabilities to off-the-shelf wheels. Figure 2 illustrates the superiority of the lowest density formulation of PORON® XRD®, 09500-65, shown in their final form in Figure 3. These wheels were tested at the highest simulated heights and recorded the lowest accelerations on impact. The first stage of the wheels, labeled as 09500-65 Disks, did not have the protruding 'Side Impact Protection' layers shown in Figure 3; these were added in the second stage as non-horizontal impacts were tested.

For further details on alternative wheel designs that did not perform as well as PORON® XRD® 09500-65, please consult Appendix C.3.

The selected wheels were subsequently given a triangular tread pattern by melting the foam. Finally, Plasti Dip® was applied to the contact surface to provide a high-traction rubber coating.

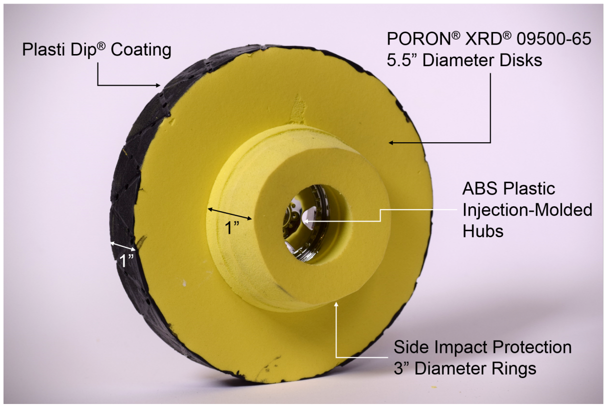


Figure 3: Mk 2 Final Wheel Design

2.2.2 Chassis

The chassis has gone through several design iterations since the PDR. The first two versions were rapid prototyped, with design changes focused on housing all components in the smallest space possible while prioritizing weight, ease of assembly, and maximizing the clearance from the chassis body to the wheel's outer diameter. Early designs were a 3D printed two-part, twist-lock design that allowed easy inner access to the middle of the chassis. While printed parts are great for experimenting with sizes and geometries, they are expensive and time consuming to print. Furthermore, printed ABS plastic parts are not design to withstand large impact forces.

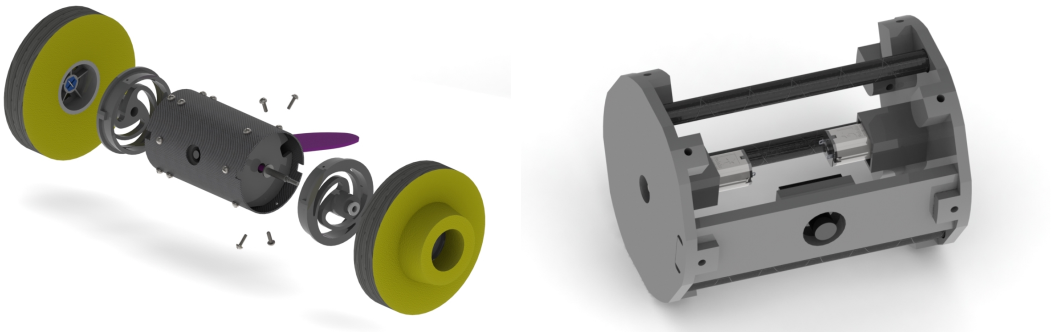


Figure 4: *Left*: Mk 2 Prototype Exploded View. *Right*: Mk 2 Prototype Inner Chassis

Moving to a light-weight, high-strength composite mitigated most of flaws found in 3D printed parts. The final chassis is a 3.125 inch diameter Kevlar-core carbon fiber tube. While this off-the-shelf component limits the possibility of complex geometry, it is approximately fifty times stronger than comparable density plastics. Additional CNC milled parts were added for an inner structure to house the electronics and outer walls to support the drive shafts, all of which are bolted to the carbon fiber tube. Finally, the removable inner structure allows assembly work to occur outside the tight confines of the carbon tube. This design change was the final step to completing the Mk 2 PoC Prototype.

2.2.3 Drivetrain

To dissipate force and simplify assembly, the drivetrain was redesigned from coupling the motor and drive shaft directly to using a flexible tube to connect the drive shaft to the the motor. Furthermore, the side walls on the carbon tube use the original suspension wheel geometry to provide some freedom of motion to the motor.

Using tubing decreased the drive shaft from a hollow half-inch shaft to a solid quarter-inch shaft. The shaft is supported at two points by low friction bushings, which are spaced out over the shaft length on both ends of an extrusion from the center of the suspension wall. Additionally, since the shafts are now in bushings and not press fit, a flange was machined on to the shafts to prevent them from being able to slide out from the chassis body. This new drivetrain is shown in Figure 5.

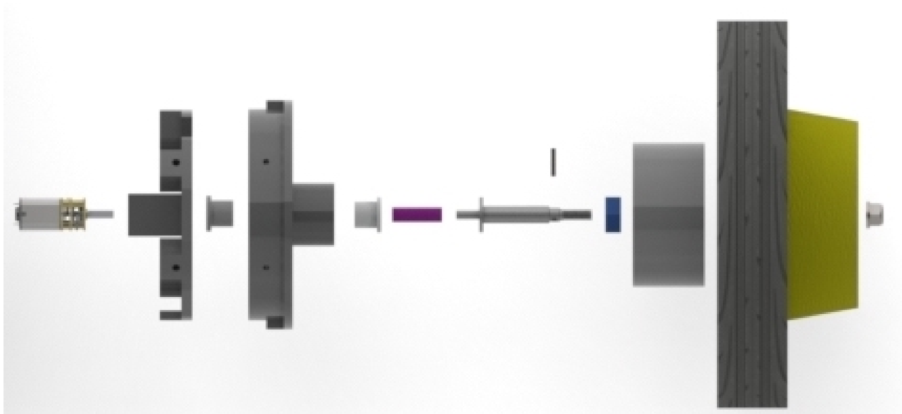


Figure 5: Mk 2 Prototype Drivetrain Exploded View

2.2.4 Tail

The tail is essential for driving as it forces the wheels to rotate rather than the chassis. It went through several designs which were tested on flat terrain, dirt, and sand. Advantages and disadvantages of the main tail categories are summarized in Table 2.1.

The selected tail is a flexible flat tail molded from PMC-790 that is five inches long and affixed to the chassis 180 degrees from the camera. It balances the flexibility needed during impact with the stiffness and weight needed to maintain the camera orientation while driving.

Tail Design	Drives Well	Lightweight	Survives Impact
Rigid Stick Tail	Yes	Yes	No
Flexible Flat Tail	Yes	No	Yes
Composite	Yes	Yes	No
Poron Tail	No	Yes	Yes

Table 2.1: Tail Comparison

Combinations of Kevlar-carbon composites and PORON® XRD® are an area for

further development; they may be capable
of absorbing the impact while maintain driving capabilities.

2.2.5 Load Path

A SolidWorks motion analysis study was conducted to determine the path of forces through the vehicle under normal conditions. As shown in Figure 6, the analysis demonstrated that the suspension wall design prevents most impact force from reaching the inner chassis. Details on modeling methodology are included in Appendix C.2.

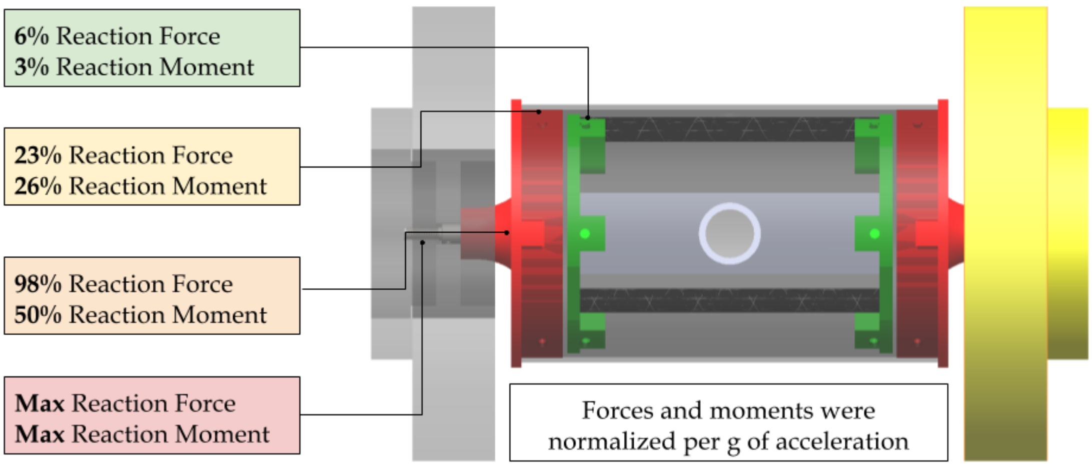


Figure 6: Load Path Analysis

2.2.6 Electronics

The components in the electronics bundle are essentially unchanged since the PDR. Excluding the battery and motors, the electronics consist of an XBee radio, an LPC1768 microcontroller, a voltage step-down regulator, a video camera with transmitter, and a motor controller. The Xbee radio receives data packets and sends them to the microcontroller where they are parsed into drive commands and sent along to the motor controller. The motor controller serves as a power amp and converts pwm signals to analog signals in order to drive the motors. These motors operate at 0-5 V and have a stall current of 700 mA at 21 oz-in.

The system power source is a two-cell lithium polymer battery that provides 5.9 Wh. The equations below show that with the two motors operating at an average of 12 oz-in, the general system power budget is around 5 W.

$$\text{Motors: } 400mA * 5V * 2 = 4.00\text{W}$$
$$\text{Camera: } 10mA * 5V = .050\text{W}$$
$$\text{Micro: } 150mA * 5V = .750\text{W}$$
$$\text{System Total: } 4.8\text{W}$$

With a factor of safety of 2 to account for higher torques and efficiency loss due to voltage regulation this results in a theoretical drive time of approximately 30 minutes.

Physically the electronics are arranged in a circular form to fit into the chassis and around the motors. The camera is mounted in the wall of the chassis in order to see out of it and the battery is placed on top of the electronics once they are fit into the inner space. This can be far more organized in the future when some parts can be condensed onto a printed circuit board (PCB) and there is more room to place mounting spots for the remaining components. The electronics are surrounded by neoprene and Sorbothane damping materials and are packed tightly to prevent damage from an impact between the components and the chassis wall.

2.2.7 Parachute Alternative

An alternative design included using a parachute to both slow the descent and prevent the PoC Prototype from landing on a single wheel. From a height of 300 feet, the robot would impact the ground at its terminal velocity of over 55 mph and experience a force far greater than the calculated maximum at which it can survive. For this reason, a drag mechanism would be required for a successful drop from such a height. After calculations for alternatives such as active or passive propellers, a guided samara, and an unfolding mechanism, a parachute was selected as the best drag mechanism for its simplicity, low weight, and ubiquity in similar applications [2]. A parachute also had the distinct advantage of delivering the robot consistently in a desired orientation. Analysis was performed (Appendix C.6) to maximize the drag-to-weight ratio such that the robot would land at a safe velocity of under 13 mph limiting the impact to around 10 g's. This design called for a 30-inch parachute (diameter) with an annular shape, resulting in a drag coefficient of 2.2. To detach from the parachute, a mini quick-release shackle was designed. The parachute was ultimately not used as the nature of the project evolved, but the design work would still be valuable, when the robot is ultimately applied at a high enough height, as a possible situational attachment option.

3 Deliverables

The Mk 2 PoC Prototypes collectively pass all FDR Threshold Specifications and several of the PSI Product Specifications. These tests prove the viability of the Mk 2 PoC final design, though the team recognizes that individual prototypes vary from vehicle to vehicle in nuanced ways. This is due to continued iteration, repeated testing, and machining by hand. The Mk 2 PoC Prototypes were all tested to the point of failure, but will be passed to PSI repaired and with spare parts and precise assembly and manufacturing instructions.

3.1 Produced Deliverables

- Four assembled AIMGRO PoC Prototypes:
  - Three Mk 2 PoC Prototypes
  - One Mk 1 PoC Prototype
  - Spare parts
- Documentation for the manufacture, assembly, and capabilities of the AIMGRO PoC Prototypes (found in listed Appendices):
  - Bill of Materials (BOM) and Vendor information
  - Final computer-aided design models (CAD)
  - Drawings, files, and written programs needed to produce all custom machined parts
  - Software library and schematic
  - Electronic schematic
  - Assembly process documentation
  - All testing data

3.2 Testing Procedure and Results

Table 3.1 characterizes the Mk 2 PoC Prototype with respect to the FDR Threshold Specification and the PSI Product Specification. The testing procedures used to quantify the Mk 2 PoC Prototype capabilities are outlined in the following subsections.

Description	Mk 2 PoC Prototype	FDR Threshold Specifications	PSI Product Specifications	Satisfied
Survivable Fall Height	35 ft	30 ft	300 ft	Threshold
Reusability	5 drops	1 drop	10 drops	Threshold
InstantEye Attachment	Rigid attachment, untested	Rigid attachment. No dangling components prior to release.	Rigid attachment. No dangling components prior to release.	Partial Threshold
System Mass	673.7 g	680 g	226 g	Threshold
System Size	100 in^3	150 in^3	45 in^3	Threshold
Drive Time	21 min	5 min	> 15 min	Product
Mobility	Navigate on flat hard ground and sand	Navigate on flat hard ground and packed dirt	Navigate on sand, dirt, as well as small obstacles up to 2 inches	Threshold
Accuracy of Drop	9 degree cone	No requirement	Land within a 20 degree cone	Threshold
Noise Emission	79.5 dB	No requirement	<85 dB	Product
Cost	$552 estimated prototype fabrication	Prototype fabrication under $3000	manufactured product should cost under $500	Threshold

Table 3.1: Mk 2 PoC Robot Testing Results Compared to Requirement Specifications

3.2.1 Drop Testing

Procedure

1. Remove electronics from Mk 2 PoC Prototype to begin test for *Mechanical Success Rate*
2. Secure prototype to string and release over a target
3. Increase height from 10 ft to 40 ft every 3 drops in 5 ft increments
4. If no mechanical failures, begin testing at 30 ft with electronics for *System Success Rate*
5. Using decibel meter, record max noise level at impact
6. Record distance from center of target to prototype
7. Drive prototype for between 30 seconds and 1 minute
8. Determine if there was a critical mission failure (i.e. loss of mobility, video, or communication)
9. Recorded number of drops until experienced critical mission failure
10. Following mission failure, characterize the next Mk 2 PoC Prototype with electronics

Results: The Mk 2 PoC Prototype succeeded in passing the FDR Threshold Specifications for Survivable Fall Height and Reusability. It also met the PSI Product Specifications for Noise Emission and Accuracy as seen in Table 3.2.

Drop Height	10-15ft	20-25 ft	30-35 ft	40ft
# of Drops	9	12	22	3
Mechanical Success Rate	100%	100%	81.82%	100%
System Success Rate	100%	100%	77.78%	N/A
Distance of Bounce (in)	3.00	16.67	32.44	23.00
Impact Noise (dB)	71.0	79.9	78.6	83.0
Tail Position	Upright	Upright	Upright	Upright

Table 3.2: Drop Testing Results

Each vehicle was tested for a minimum of six drops, with the first Mk 2 PoC Prototype (Mk 2-1) completing 19 drops ranging from 5 ft to 40 ft without electrical components. The second and third Mk 2 PoC Prototypes (Mk 2-2 and Mk 2-3 respectively) were integrated with the electronics. Electronic failure defines the difference between *Mechanical Success Rate* and *System Success Rate*, with *System Success Rate* quantifying whether both mechanical and electrical components continued working after the drop. There were 23 total drops at or above the threshold height of 30ft, with success rates listed above. Mk 2-1 was dropped from 10 to 30 ft and failed on drop 15. Mk 2-2 failed after 11 drops incrementing from 10 to 30 feet. Testing for Mk 2-3 started at 35 ft and encountered critical failure after six drops at that height. Table 3.3 shows the failure modes and the rate of occurrence over the 50 drops from heights of 1 ft to 40 ft. The results of each individual trial are in Appendix B.

Each prototype survived at least the single-drop FDR Threshold at greater than 30 ft, but none reached the PSI Product Specification of 10 successful drops in a row. The average noise level of 79.5 dB passes the PSI objective of 85 dB maximum impact noise. In addition, the distance of bounce measurements above all fall within the nine degree cone defining the PSI accuracy objective. Finally, an InstantEye attachment was designed and produced, but was unable to be tested on the InstantEye payload due to lack of access. Therefore no definitive statement can be made regarding meeting this specification, but the attachment does fit on the ground robot and fits perfectly in the CAD model.

Failure Modes	Electronic Component	Pin Connection	Drive Axle	Wheel Hub	Tail Detachment
Over all 43 Drops	1	1	2	1	2
Rate of Failure	2.3%	2.3%	4.7%	2.3%	4.7%

Table 3.3: Testing Failure Modes

3.2.2 Mobility Testing

Procedure

1. Drive Mk 1, 2 PoC Prototypes on hard flat ground
2. Drive Mk 1, 2 PoC Prototypes on loose surfaces (i.e. sand, dirt)
3. Drive Mk 1 PoC Prototype over small 90 degree foam-core steps
4. Record time from start until battery died

Results: The Mk 2 PoC Prototypes exceeded FDR thresholds and PSI final product specifications with a 21 minute drive time. It was most successful on flat surfaces such as concrete and could handle small obstacles around a quarter inch tall. Therefore the Mk 2 meets the FDR Threshold mobility specifications, but does not fulfill the PSI final product mobility specifications. Additionally, the Mk 1 PoC Prototype, which has the same drive train and mobility functionality, was able to drive on flat sand and loose-dirt surfaces, meeting the loose surfaces component of the PSI Product Mobility specifications.

3.2.3 Physical Characterization

- **Mass:** The average Mk 2 PoC Prototype had a mass of 673.7 g which fulfills FDR threshold specifications, but not the PSI Product specifications of 226 g. The final prototype, the Mk 2.3, has a mass of 674 g which is the only prototype to include the InstantEye attachment interface.
- **Size:** The Mk 2 PoC Prototype has a volume of 100 in^3 which fulfills FDR Threshold Specifications, but not the PSI Product Specification of 45 in^3.
- **Cost:** The Mk 2 PoC Prototype has an estimated cost of $552 which fulfills the FDR threshold but barely does not meet the PSI final product cost specification of under $500. The breakdown of this calculation can be found in Section D on Economic Analysis.

3.3 Risk Assessment

Over the course of this project, there were many obstacles to success. Conversations with faculty advisors and failure mode analyses helped to identify potential risks. The FMECA in Table 3.4 shows the three failure modes that are most likely to impede success: vehicle drive time, ability to be lifted by the IE air vehicle, and ability to survive the drop from the IE air vehicle.

Function	Failure Mode	Effects	Cause	Control Method	RPN SCORE
Lifted by the IE	• Vehicle is too heavy • Interferes with IE airflow	• IE cannot take off with the vehicle • IE cannot safely fly with the vehicle	• Chassis is too heavy • Too much surface area below the IE	• Light components • PCB electronics • Lighter drop mechanism	160
Survives the drop	• Vehicle shatters • Damaged electronics • Shaft shearing	• Vehicle cannot drive • Vehicle is uncontrolled • Vehicle cannot relay video	• Chassis impacts the ground • Driveshaft shears	• Wheels are outermost part of the vehicle	144

Table 3.4: Critical Failures and their Prevention

These two failure modes were both prevalent obstacles to success. Drag mechanisms were eliminated to enhance concealment and fall accuracy, however this made fall survival more hazardous. Early vehicle prototypes did not survive falls from even 20 ft, leading to significant design changes to mitigate this impact failure mode. To compensate for the elimination of the parachute, the parts became more robust to increase the structural integrity resulting in an increased mass.

3.4 Difference from the State of the Art

Several patents exist for technologies that could fulfill design requirements similar to both the threshold and final product specifications. However, many of these patents are specific to a certain use-case, or robot. Relevant patents were scrutinized for their methods for dropping, augmented mobility, and size and weight constraints, such as the high velocity impact survivability of the non-pneumatic Spirit and Opportunity Mars rover wheels. Many of these technologies met or even exceeded certain specifications, however none simultaneously met every requirement. A list of relevant patents is available in Appendix D.

3.5 Discussion of Assumptions

- Components were designed to minimize impact forces on the axle to prevent bending.
  - Assumed in single wheel impacts that increased force is negated by the impact angle that decreased distance from force to a fixed point on the axle
  - Several drive shafts bent during testing proving these assumptions to be false
  - New calculations are necessary to determine maximum bending force for a given angle between zero and ninety degrees
- A drag mechanism is necessary to prevent uncontrolled free-fall and ensure two-wheel impact which has an acceleration of 50 g's at impact rather than a one-wheel impact which gives an acceleration of 80 g's.
  - ShockWatch® devices affixed to the prototypes during testing showed the robots experienced accelerations in excess of 75 g's
  - Slow-motion footage confirmed that one-wheel impacts were significantly more common than two-wheel impacts without controlled free-fall
- Preventing one-wheel impacts will definitively increase survivability
  - Reduces force and bending moment on axle, a common failure mode
  - Reduces acceleration on robot as a whole which reduces force on electronics, another common failure mode

4 Economic Cost Analysis

Current estimates from aerospace and defense industry market analysts place the total available market for UAVs of all sizes at $2 billion and growing to $6.8 billion by 2025 [4]. According to PSI's Vice President Thomas Vaneck:

- There is a serviceable available market of 70 thousand small UAVs
- Assuming that one AIMGRO will sell for every five IE small UAV packages (including air vehicle, ground control station, etc.), the robot will have a service available market of approximately 14 thousand units
- PSI currently holds 80% of the market, but expects to hold 40-50% of the market in the long term

The target market for AIMGRO is roughly 6 to 7 thousand units and, with PSI currently projecting to sell AIMGROs for $1,500 each, this gives the product a target market of $8-11 million, not including additional market opportunities such as training, repairs, and/or miscellaneous payloads.

Currently, the major manufacturers and suppliers associated with the project are: SparkFun, Pololu, and ARM mbed for the electronics; Dragonplate Composites for the chassis; and Rogers Corporation for the PORON® XRD® foam. However, these are all subject to change as PSI scales and refines the design to use different components (e.g. creating a PCB to replace the current electronics).

The primary costs associated with the project are the procurement of raw materials and parts, and paid labor for the assembly and manufacture of the robot. Current cost estimates place the raw material and parts cost for a single AIMGRO vehicle at approximately $327 ($220 for electronics and $107 for non-electronic components). Based on the current design's production process, building of an AIMGRO robot will take roughly 5 hours of machining and assembly time. Assuming the standard contracted pay of $45 per hour for equipment and machining, this would cost $225 [1]. Therefore, the total cost for production of a single AIMGRO robot is approximately $552.

However, as production scales up to over a thousand units, bulk discounts from materials and parts suppliers begin to make an impact. Assuming a typical discount of 10%, this implies a decrease in material cost for non-electronic components from $107 to $96 [3]. Assuming assembly line procedures would decrease time and remove overhead for renting CNC equipment, switching to these procedures could reduce labor costs to $113. This would yield a final cost of $219 per vehicle.

5 Recommendations for Future Work

The priority for this project was achieving basic functionality and meeting all the thresholds before moving forward. There are many potential improvements that can be made in the immediate future of the AIMGRO project. These future plans aim to build off of this project's success as a proof of concept and further develop it into something more robust and easy to use. The primary goals for new prototypes are testing the interface with the InstantEye air vehicle, cutting size and weight from both the electrical and mechanical systems, improving ease of use, and enhancing the top end functionality for both mobility and survivable drop height.

Future work for this project will be continued by PSI in the manner they deem most fit, either by developing internally or outsourcing to a design firm. The complete documentation needed for the continuation of the project (including the PoC robot's manufacturing and assembly processes as well as its performance capabilities) is included as one of this project's main deliverables as outlined in Section 3.1 of this report.

5.1 System Interface

Drop testing from the InstantEye air vehicle did not happen in the timeline of this project, the current design attaches to the air vehicle but has not been tested as an integrated system. An immediate addition would be testing the interface for attaching to the linear servos on the InstantEye's existing dropping mechanism. A design of the feature is included in the deliverables along with a fabricated initial version.

5.2 Electrical

One of the first improvements to the system should be shrinking the form factor of the electronics and adding a switch to the system. Although the AIMGRO system is intended for use in the field where the robot will likely run until the battery dies, a switch will be very convenient for demo purposes. The electronics drive the size constraints of the chassis and developing a small PCB or set of PCBs will allow for a smaller inner and outer chassis, and thus greatly decrease overall weight. Eventually this lighter vehicle could allow for lower power motors and a smaller battery as well. The electronics should also be updated with a low-power processor such as the Cortex-M0+ which can be powered by 3.3 V as opposed to 5 V.

The motor controller and radio are the limiting factors to shrinking the electronics because they cannot be made smaller. However, if necessary the motor controller can be removed by using a custom power amp and multiple digital-to-analog converters on the microcontroller. Once these decisions are made and a PCB is in place, PSI could manufacture a custom battery of potentially half the weight and size of the existing battery. Between the changes to the electronics and the battery, there is a lot of room to shrink the entire robot and move towards the target weight of 226 g.

5.3 Mechanical

There are several key mechanical challenges going forward that could improve the overall efficiency and effectiveness of the robot.

- Scaling down the robot size and mass while simplifying construction.
  - Simplifying the inner chassis to a single injection molded part.
    - 3D printing requires substantial mass increases to achieve necessary structural integrity due to the inherent weaknesses in printed parts.
  - A smaller ground robot would require less torque to drive, enhancing the mobility capabilities of the current motors or allowing for lower-power motors.
  - Modifying the current mating of inner chassis to outer chassis from 20 screws to no screws by a twist and lock mechanism.
    - Easier to (dis)assemble for demonstrations while replacing mass of screws, washers, and nuts with a lighter-weight alternative.
    - Removing supports for the screws in the inner chassis walls would significantly cut the weight of those parts.
- Increasing survivability by changing material selection
  - Moving to composites, foams, or other advanced materials out of this project's manufacturing scope could result in decreased weight while maintaining or even increasing structural integrity.
  - Use of lightweight materials could allow for unique forms that would decrease weight and size, or increase drag and lower the terminal velocity.

By implementing some of these recommendations, the product could be lighter, smaller, easier to use, and ready for deployment in field testing. This product will enhance the capabilities of the InstantEye system as a whole, providing users with an entirely new surveillance tool.

6 Acknowledgements

The AIMGRO Project would not have been possible without hours of support and guidance. The team would like to thank everyone at PSI Tactical Robotics for the opportunity to learn about advanced robotics. Thank you to the Rogers Corporation, Sorbothane Incorporated, and ShockWatch for providing free product samples that made this project possible. Thank you to the Thayer School Staff, notably Jason Downs, Kevin Baron, and Callen Votzke for supporting us. Thank you to Professor Douglas Van Citters for your constant support and guidance. Finally, thank you to Professor Solomon Diamond and Professor Laura Ray for advising us throughout this entire process.

References

[1] C. (n.d.). Retrieved March 03, 2017, from http://cncmachinisttraining.com/2013/08/16/machine-shop-rates-whats-the-average-hourly-rate/

[2] Kellas, A. (2007). The guided samara: design and development of a controllable single-bladed autorotating vehicle (Doctoral dissertation, Massachusetts Institute of Technology). Web. 03 Dec. 2016.

[3] Lowe's ProServices: Buy in Bulk. (n.d.). Retrieved March 03, 2017, from https://www.lowes.com/cd_Lowes Commercial Services Buy in Bulk_577249990_

[4] Zoretich, Tom. "Teal Group Predicts Worldwide Military UAS Production Will Total $70 Billion in Its 2016 UAS Market Profile and Forecast - Teal Group Corporation: Aerospace and Defense Market Intelligence — Analysis and Forecasts." N.p., n.d. Web. 08 Nov. 2016.

A Overview

Figure A1: Rendering of Mk 2 Prototype attaching to IE drop mechanism

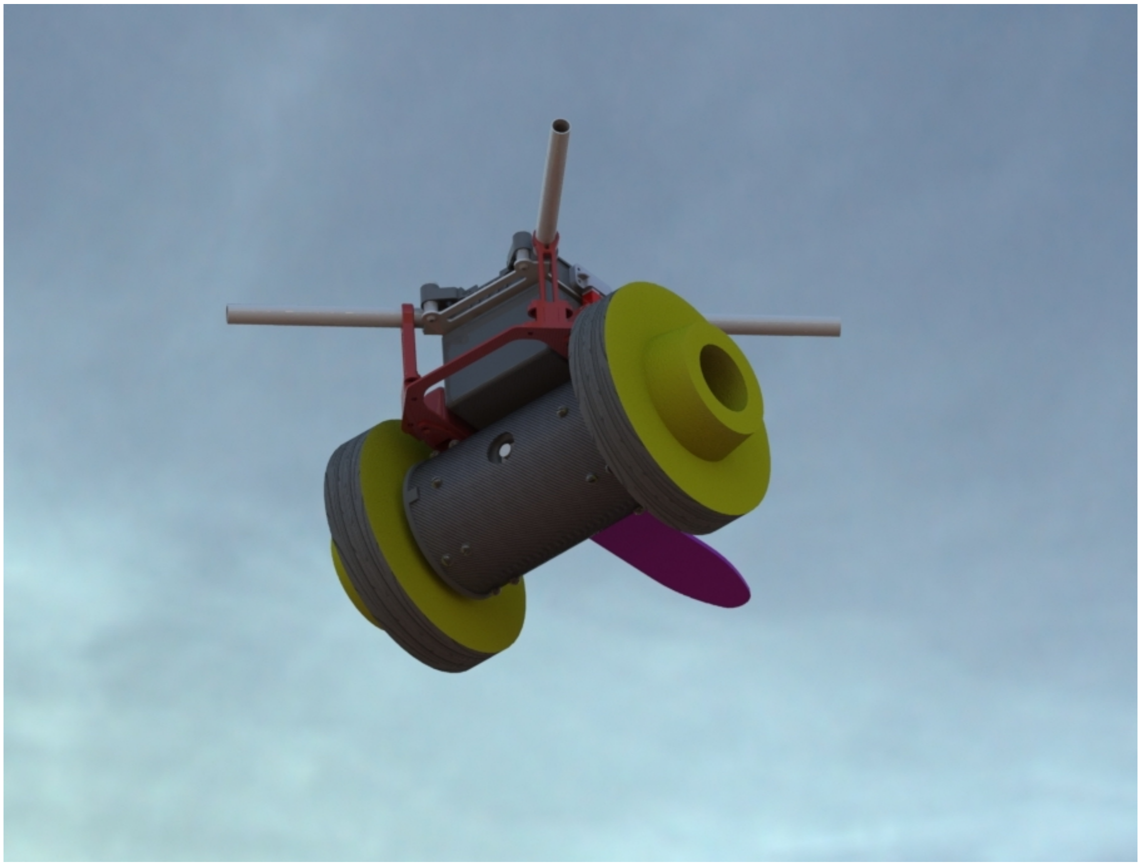


Figure A2: Rendering of Mk 2 Prototype attached to IE drop mechanism

B Testing Results

Bot	Sizing		Mobility	Dropping			
	Mass (g)	Size (in^3)	Drive Time (min)	Angle from Drop Axis (deg)	Max Drop Height (ft)	Drops before Failure	Noise Level (dB)
Mk1 - 1	550.9	100	21	N/A	N/A	N/A	N/A
Mk2 - 1	671.3	100	21	3.6	40	8*	78.1
Mk2 - 2	675.9	100	20	5.8	30	4	N/A
Mk2 - 3	674.0	100	21	4.6	35	6	82.8
Min	671.3	100	20	3.6	30	4	78.1
Average	673.7	100	21	4.7	35	5	80.5
Max	675.9	100	21	5.8	40	6	82.8
	* no electronics in robot						

Figure B1: Summary of Testing Results

Bot	Drop Height (ft)	Drop #	Impact Noise (dB)	Distance from Center Mark Final Landing Spot (in)	Angle from Drop Axis (deg)	Mission Critical Failure (Y/N)	Failure Mode (LM,LC,LV,MF)	Failure Mode Notes
Mk2 - 1	10	1	69.0	5	4.77	N		
	10	2	68.6	3	2.86	N		
	10	3	75.4	1	0.95	N		
	20	4	84.2	21	10.00	N		
	20	5	77.4	22	10.47	N		
	20	6	78.0	7	3.34	N		Bent driveshaft, still functioning
	30	7	66.0	18	5.72	N		
	30	8	68.0	24	7.63	Y	LM	Plastic hub snapped off of axle
	30	9	61.0	45	14.25	N		
	35	10	83.0	24	6.54	N		
	35	11	85.6	26	7.08	N		
	35	12	82.6	35	9.53	N		
	40	13	80.4	30	7.15	N		
	40	14	86.7	23	5.49	N		
	40	15	81.9	16	3.82	N		
Mk2 - 2	30	1	N/A	36	11.42	N		
	30	2	N/A	38	12.05	N		
	30	3	N/A	39	12.37	N		
	30	4	N/A	32	10.16	Y	LM	Lost pin connection to voltage modulator
Mk2 - 3	35	1	81.9	36	9.80	N		
	35	2	81.5	26	7.08	N		
	35	3	80.4	48	13.04	N		
	35	4	85.4	59	15.99	N		
	35	5	85.2	14	3.82	N		Able to drive after a short hesitation
	35	6	82.6	19	5.18	Y	LM	Unable to drive after impact

Figure B2: Drop Testing Results

C Design and Development

C.1 Failure Mode, Effects, and Criticality Analysis

Function	Failure Mode	Effects	Cause	Control Method	RPN	Action Plan
Attaches to the IE Drop Mechanism	• Does not interface with the dropping mechanism • Cannot fit under the IE	• Vehicle cannot attach to the IE • IE cannot take off with the vehicle	• No interface • Wheels are too big • Chassis length	• Design an interface • Keep overall size small • Design new drop mechanism	72	
Lifted by the IE	• Vehicle is too heavy • Interferes with IE airflow	• IE cannot take off with the vehicle • IE cannot safely fly with the vehicle	• Chassis is too heavy • Too much surface area below the IE	• Light components • PCB electronics • Lighter drop mechanism	160	Reduce size of electronics to reduce the size (and mass) of other components, redesign the drop mechanism
Fall straight to the landing surface	• Tumbling • Impact with other surfaces	• Vehicle crashes • Side impact damage	• Vehicle begins swinging on deployment • Dropping in obfuscated areas	• Deploy from stationary UAV • Keep wheels as the most prominent surface	160	Reinforce the sides of the wheels, make tail out of a flexible material
Survives the drop	• Vehicle shatters on impact • Electronics are damaged • Shaft shearing	• Vehicle cannot drive • Vehicle cannot be controlled • Vehicle cannot relay video	• Chassis impacts the ground • Driveshaft shears • Impacts the tail	• Wheels are the max diameter • Direct impact forces to chassis • Create a wide tail to flip up in the fall	144	Test drop heights incrementally, reinforce parts subjected to extreme stress, shield the electronics from impact forces

Figure C1: FMECA for Dropping

Function	Failure Mode	Effects	Cause	Control Method	RPN	Action Plan
Communicate with computer	• Signal does not reach computer • Signal does not reach vehicle	• Vehicle cannot move	• Physical signal obstruction	• Bench testing • Signal transmission through the IE	3	
Drives 10 minutes on the ground	• Cannot drive for 10 minutes	• Vehicle cannot move far	• Insufficient battery powe • Overheating	• Choose battery to match power budget with factor of safety	36	
Relays Video	• Video transmission fails	• Visual data not relayed	• Camera broken on impact • Video signal is out of range	• Test camera functionality • Design to protect camera on impact	36	
Drives on flat hard surfaces	• Cannot move forward • Cannot turn	• Vehicle is stationary • Vehicle cannot move quickly	• Insufficient traction • Low motor torque • Insufficient battery • Tail drags	• Increase wheel traction • Increase battery capacity • Increase electronics efficiency • Decrease tail friction	72	
Drives on loose surface	• Cannot move forward • Cannot turn	• Vehicle is stationary • Vehicle cannot move quickly	• Insufficient traction • Low motor torque • Insufficient battery • Tail digs in	• Increase surface area of the wheels • Increase wheel features that can grab the substrate • Design a wide tail	100	Test tail and wheel designs on a test robot before integrating with the vehicle

Figure C2: FMECA for Electronics and Driving

C.2 Force Path

A SolidWorks motion analysis study was conducted to determine the path of forces through the vehicle under normal conditions. Initially only a normal gravitational force was applied, with the wheels fixed; when additional acceleration was applied, forces scaled directly. Reaction forces and moments were calculated at four key interfaces by selecting the appropriate mates between those interfaces.

Force dispersion is accounted for in material displacement. As defining the material properties for several of the components (for instance, the Poron wheels) is beyond the scope of the project, results cannot be examined for their exact values. The analysis was instead interpreted for general trends. To allow the model to solve, the structure was simplified by removing fasteners, electronics, drive train tubing, and the motors. To replace these components, a dummy mass was added.

The absolute value of the results were taken, and moments were rounded to the nearest N-mm to remove rounding errors.

	Force per g (N/(m/s^2))			Moment per g (N-mm/(m/s^2))		
Orientation:	**X**	**Y**	**Z**	**X**	**Y**	**Z**
Wheel-Shaft	0	5.2	0	180	0	0
Shaft-Outer Wall	0	5.1	0	91	0	0
Outer Wall to Chassis	0	1.2	0	47	0	0
Chassis to Inner Wall	0	0.33	0	7	0	0

Table C.2.1: Reactions at Contact Points

There is some additional error from mass discrepancies, again because of material properties and slight design changes.

Component	Quantity	Real Mass (g)	SW Mass (g)
Carbon Fiber Chassis	1	61.3	86.11
Suspension Walls	2	36.4	40.37
Inner Walls	2	35.2	34.98
Carbon Fiber Rods	3	2.5	2.72
Camera Wall	1	11.9	16.35
Poron Wheels	2	71	75
Steel Shafts	2	8.8	9.14
Mass Dummy	1	N/A	175

Table C.2.2: Compare Mass in the SolidWorks Model to the Physical System

C.3 Wheels Development

The other wheels developed included several varieties of PORON® XRD® formulations as well as an off-the-shelf pneumatic wheel. An earlier version of the PORON® XRD® low-density wheels were formed by layering strips of material (09500-65 Strips); higher density PORON® XRD® was tested by layering strips (15500-65 Strips); machined nylon "suspension wheels" were designed to deflect upon impact with a PORON® XRD® 12500-65 core; pneumatic model aircraft wheels; and a control in which the pendulum impacted at a height of X ft without any wheel damping.

Figure C.3.1: Wheels from left to right: PORON® XRD® 15500-65 Strips; the original Nylon Suspension Wheel; Nylon Suspension Wheel with PORON XRD 12500-65 inserts; (above) 09500-65 Disks with Side Impact Protection; (below) 09500-65 Strips with Side Impact Protection; Pneumatic Wheels; Final PORON® XRD® 09500-65 Disk Wheels.

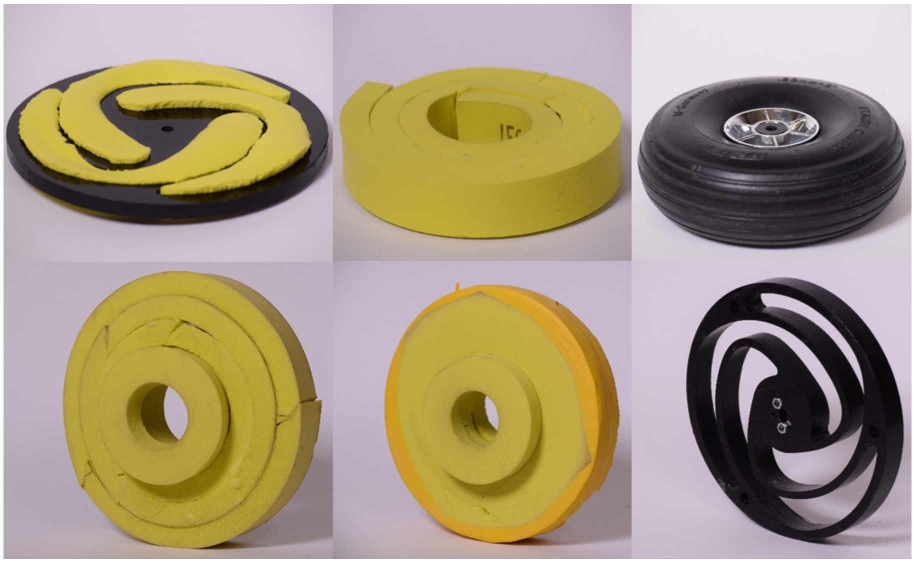


Figure C.3.2: Wheels from left to right: Row 1: Nylon “Suspension Wheel” with PORON® insert, 15500-65 Strips, Pneumatic; Row 2: 09500-65 Strips with Side Impact Protection, 09500-65 Disks with Side Impact Protection, and the original Nylon Suspension Wheel.

C.4 Tail Development

Tail Weighting

As an unstable vehicle, weighted tails help to maintain the trajectory of a two-wheeled robot. To return to the intended path, the moment caused by a wheel and the drag on the tail must overcome the moment caused by the other wheel about the center of mass, as shown in figure C4.1.

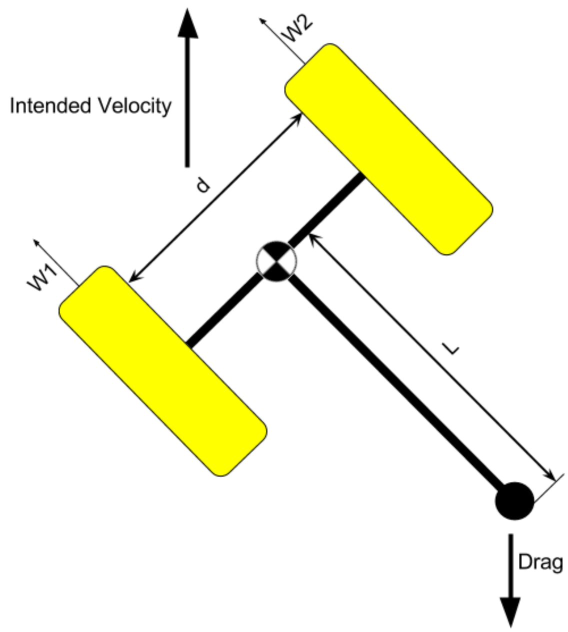


Figure C4.1: Diagram of the vehicle off of its intended path

This is represented mathematically as

$$W_1 * \frac{d}{2} + T * L * sin(\theta) = W_2 * \frac{d}{2}$$

If motors are functioning normally,

$$W_1 = W_2$$

so that any non-zero drag from the tail will help to maintain the course. Heavier tails will perform better at this. However, due to the extreme need to minimize mass, it was determined that the costs of the added (potentially compromising the flight of the UAV) were greater than the benefit of more stable drive trajectories.

This also means that the tail flips over the robot in the event of sudden deceleration or turning. This is not a significant problem; the tail was positioned directly across from the camera, so that the viewing angle will be equivalent regardless of the tail orientation. It was also discovered that allowing the tail to lift is a for turning on loose terrain; the tail does not drag in the substrate, allowing for increased turning efficiency.

Tail Length

There were conflicting elements in determining the ideal tail length. While short tails minimize turning drag and are less likely to become entangled in the environment, longer tails can minimize drag in normal forward movement. Several mock-up tails were tested on hard terrain and sand, by affixing them to a small test vehicle made of servo motors, a battery, and a flat platform. Longer tails performed better on loose surfaces, as shown in Table C4.2 below, where tail performance is ranked from no functionality (0) to working perfectly (3).

Type	Length	Steps	Flat Drive	Flat Turn	Dirt Drive	Dirt Turn	Sand Drive	Sand Turn	Total Score
Flat Sheet	2"	0	3	3	1	3	0	3	13
	3"	1	3	3	2	3	1	2	15
	4"	2	3	3	3	2	2	1	16
Wire Loop	2"	0	3	3	2	1	1	3	13
	3"	2	3	3	3	2	3	1	17
	4"	2	3	3	3	1	3	0	15
Wire Stick	2"	1	3	3	2	1	1	2	13
	3"	1	3	3	1	2	3	3	16
	4"	2	3	3	2	1	3	2	16

Table C4.2: Comparison of tail designs

Because of these results, we decided on a longer tail. Some additional length was added to account for the flexibility of the plastic material selected. As discussed in the body of the report, the flexible flat sheet tail was selected to reduce the risk of shattering on impact. Figure C4.3 shows the PoC prototype tails, which were given color to increase visibility in demonstrations.

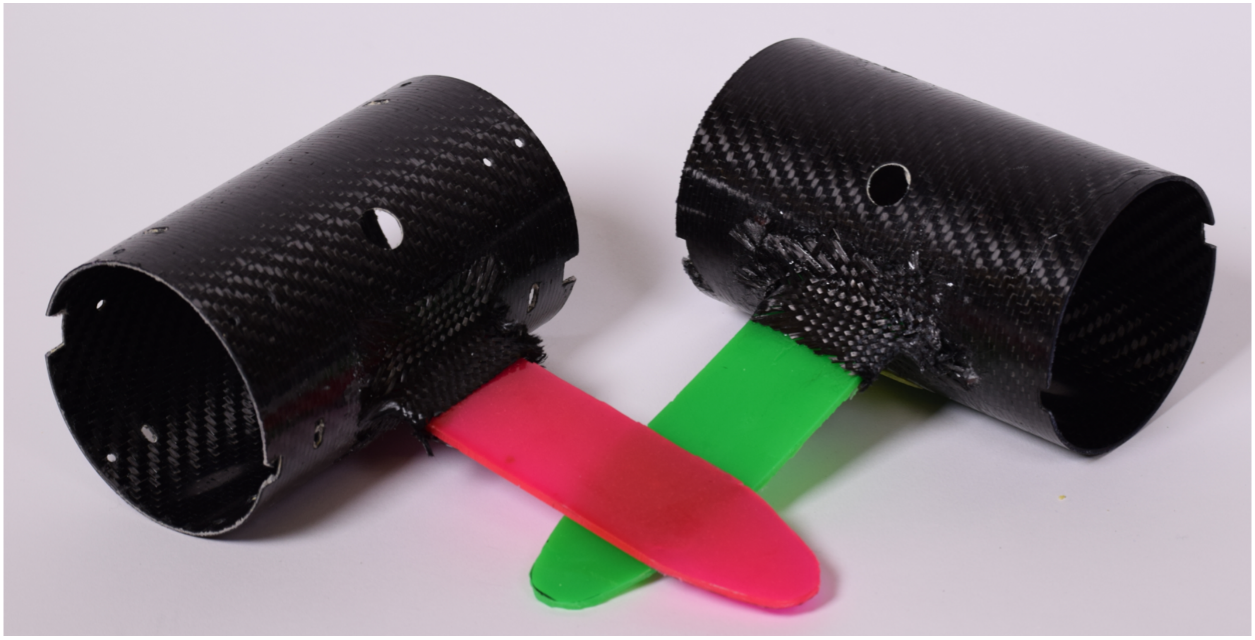


Figure C4.3: Two flexible PMC-790 plastic tails with carbon fiber chassis attachment

Tail Attachment

The tail is affixed to the body using Liquid Nails adhesive and carbon fiber sheets. Future work could look into adding a hole insert for the tail in the chassis. While there was some electronics housing from sliding into the carbon tube. experimentation in creating tails with tabs that inserted into a hole in the chassis (diagram in Figure C4.4) these were not used in the Mk 2 for two reasons. Firstly, the connection was not tight enough to be maintained during impact (the tail popped out) and secondly, the tail could not be permanently affixed to the body within its placement hole because it prevented the electronics housing from sliding into the carbon tube.

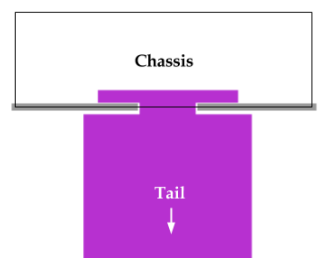


Figure C4.4: Diagram of a tail with tabs

Potential Future Work There is a great deal of room for tail development. Composite tails, which combine a short, light, rigid piece with a flexible component, have great potential– the majority of the weight could be placed at the end of the tail. Flaps could be included, which could help serve as a drag mechanism for the entire vehicle and influence correct landing orientation.

C.5 Electronics and Software Development

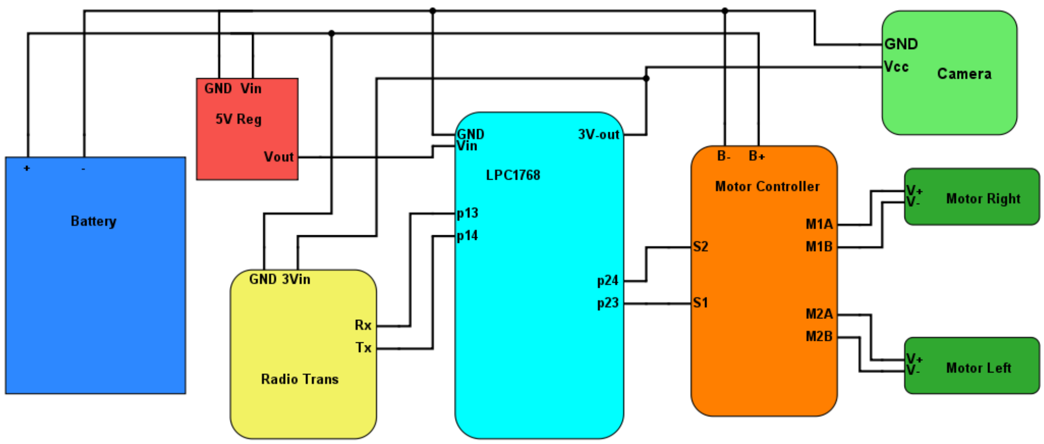


Figure C5.1: AIMGRO Circuit Schematic

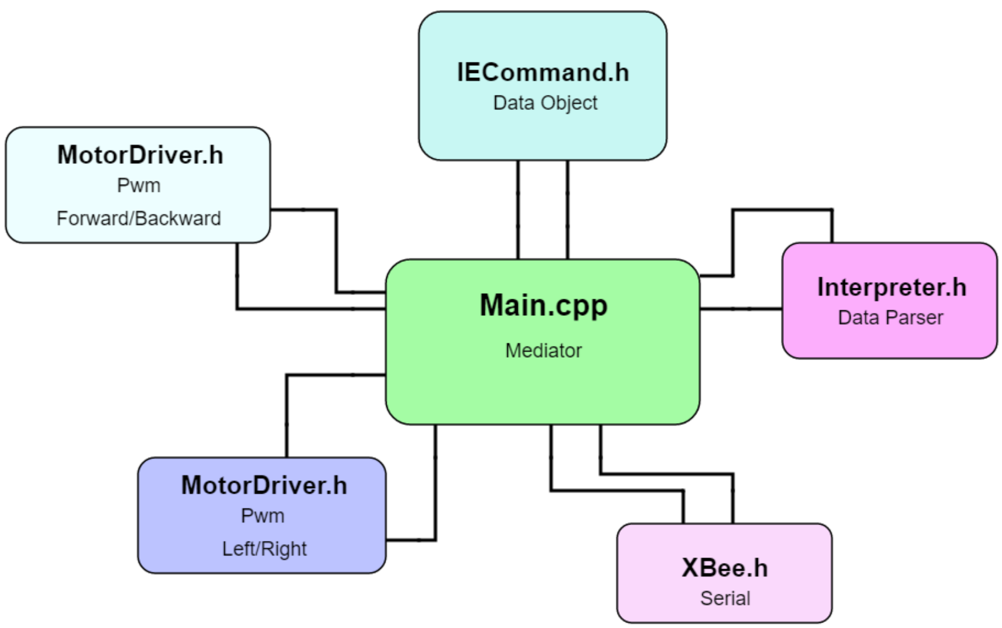


Figure C5.2: AIMGRO Software Schematic

C.6 Parachute Development

$$Terminal\ Velocity = \sqrt{\frac{2mg}{Cd * p * A}}$$

$$Velocity\ with\ Parachute = \sqrt{\frac{8mg}{\pi * r * Cd * D^2}}$$

Target Mass: .500 kg (1.1 lbs)
Parachute Shape: Annular
Coefficient of Drag: 2.20
Weight of Parachute: 46.1 (.102 lbs)
Diameter of Parachute: 15 in
Area Canopy: 8.47 ft^2
Cd Area of Parachute: 1.24 ft^2
Gravity: 32.2 ft/s^2
Density Air: .00238 slug/ft^3

$$Predicted\ Parachute\ Terminal\ Velocity = 10.24\frac{ft}{s} = 3.12\frac{m}{s}$$

$$\frac{\Delta v}{\Delta t} = a \qquad \frac{3.12\ m/s}{0.03\ s} = 104\frac{m}{s^2} = \mathbf{10.6\ gs}$$

$$F = \frac{m\Delta v}{\Delta t}$$

$$Predicted\ Impact\ Force = \frac{\left(0.5\ kg * 3.12\frac{m}{s}\right)}{.03\ s} = \mathbf{52\ Newtons}$$

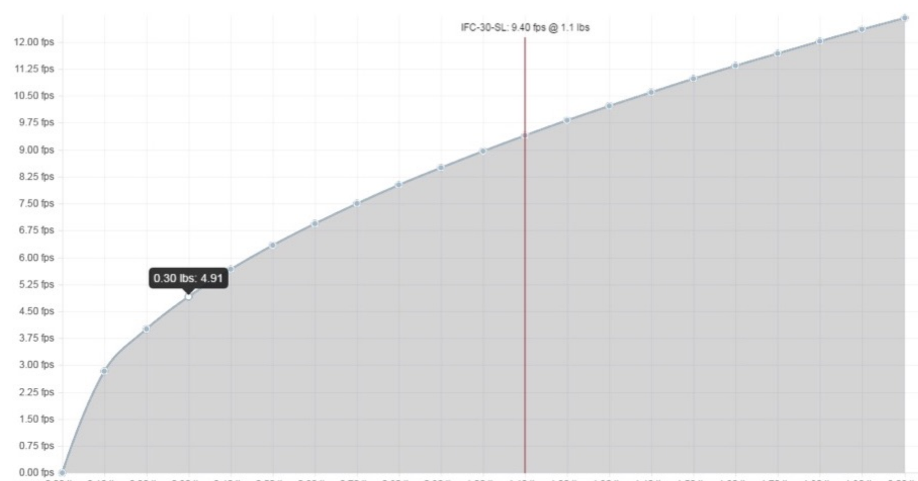


Figure C6.1: Parachute Calculations

D Economics

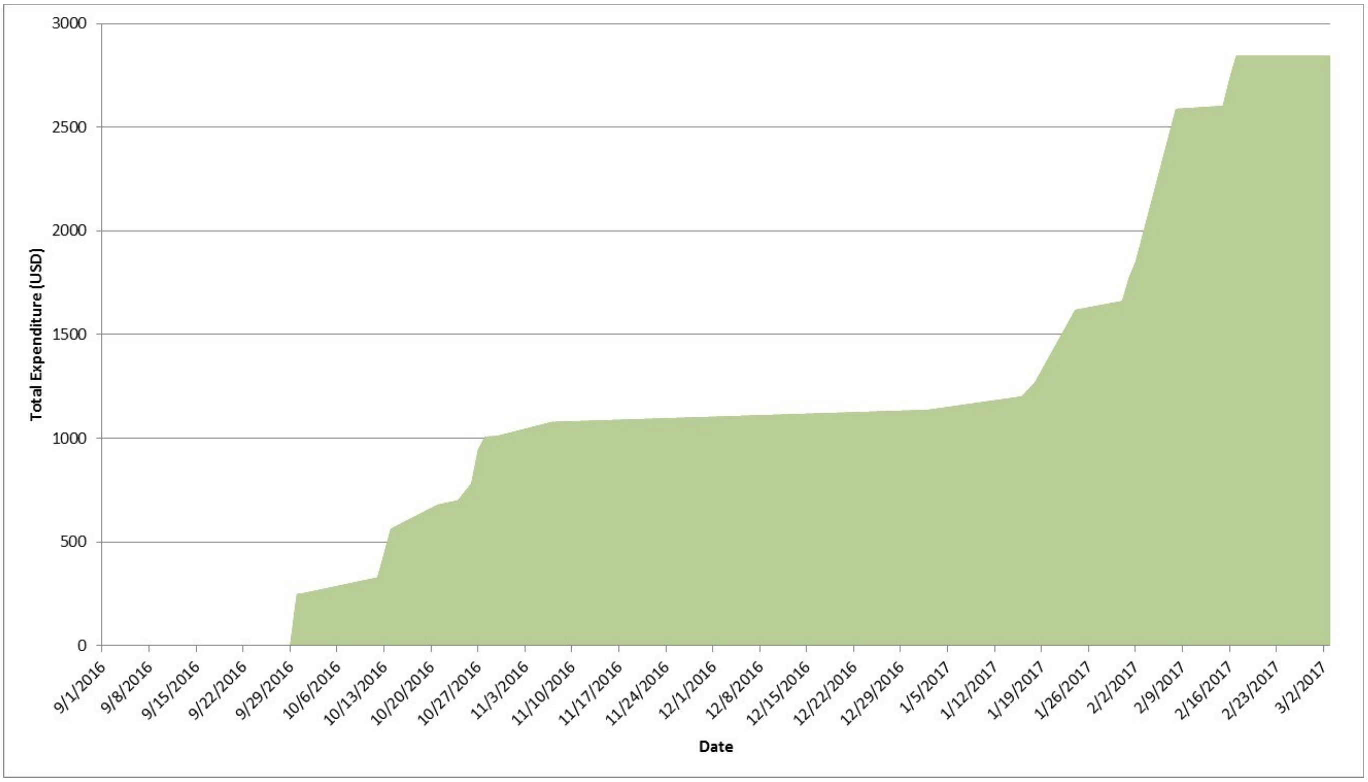


Figure E1: Cumulative Expenditure

Users in Thousands		
Army Active Duty [1]	460	
Army Combat Arms [2]	69	
Army Squads [3]	8	
Marines Active Duty [1]	180	
Marines Combat Arms [2]	27	
Marines Squads [3]	2	
Air Force Active Duty [1]	320	
Air Force Special Warfare [4]	18	
Air Force Squads [3]	1	
Navy Active Duty [1]	330	
Navy Special Warfare [4]	9	
Navy Platoons [3]	1	
Total Users	12	
Number of IE's per "User"	*3*	
Total IE's for US DoD	35	
Ratio USDoD:Internation & Professional	*1*	
Ratio of IE:AIMGRO	*5*	
PSI Serviceable Available Market (SAM)	**Units (000s)**	**Value (MM)**
InstantEye	70	561
AIMGRO	14	21
PSI Long-Term Market Share	*40-50%*	
PSI Target Market (TM)	**Units (000s)**	**Value (MM)**
InstantEye		
40%	28	224
50%	35	281
AIMGRO		
40%	6	8
50%	7	11

[1] Press Operations. "Department of Defense (DoD) Releases Fiscal Year 2017 President." U.S. DEPARTMENT OF DEFENSE. U.S. Department of Defense, n.d. Web. 09 Nov. 2016.

[2] Estimated 15% of active duty personnel are in combat operations

[3] Army Squads are 9 soldiers, Marine/Air Force Squads are 13 marines/airmen, Navy Platoons are 16 sailors

[4] United States Government Accountability Office. "SPECIAL OPERATIONS FORCES Opportunities Exist to Improve Transparency of Funding and Assess Potential to Lessen Some Deployments." GAO, July 2015. Web.

Figure E2: Market SAM and TM Calculations and Assumptions

Patent Number	Patent Holder	Patent Claim
9,216,510	iRobot	Control Arms & Manipulators
9,195,256	iRobot	Controller for robot
8,527,113	iRobot	Modular UGV that can be “detracked” to reach speeds in excess of 6mph
8,884,763	iRobert	Threat detection suite for robot
7,775,305	Sandia Corporation	Wheeled hopping robot to overcome obstacles relatively large in size to the robot
9,150,069	Illinois Institute of Technology	Hybrid aerial and terrestrial robot ~ quadcopter inside a cylindrical birdcage for rolling
9,283,681	Tobor Technology	Modular vehicle for inspecting remote locations with collapsible treads and onboard video system
8,996,244	Harris Corporation	IED defeat system using remotely controlled macro and micro arms
7,235,046	Science Applications International Corporation	Toroidal propulsion system
7,076,338	Sony	Basic walking robot automation
9,195,233	Perrone Robotics	General purpose robotics operating system

Figure E3: List of Relevant Patents

E Deliverables

E.1 CAD Renderings

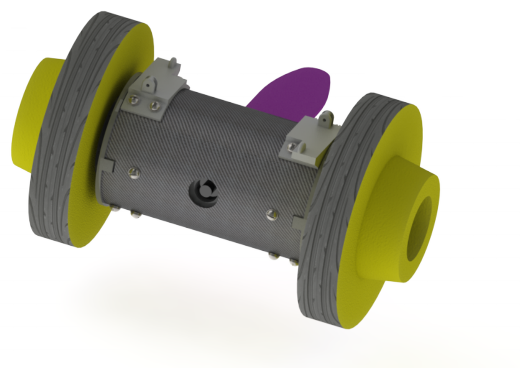


Figure E1: Mk2 Prototype Isometric CAD

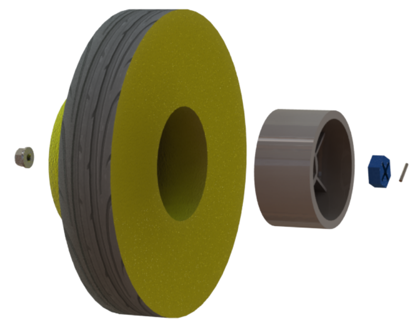


Figure E2: Mk2 Prototype Exploded Wheel Assembly

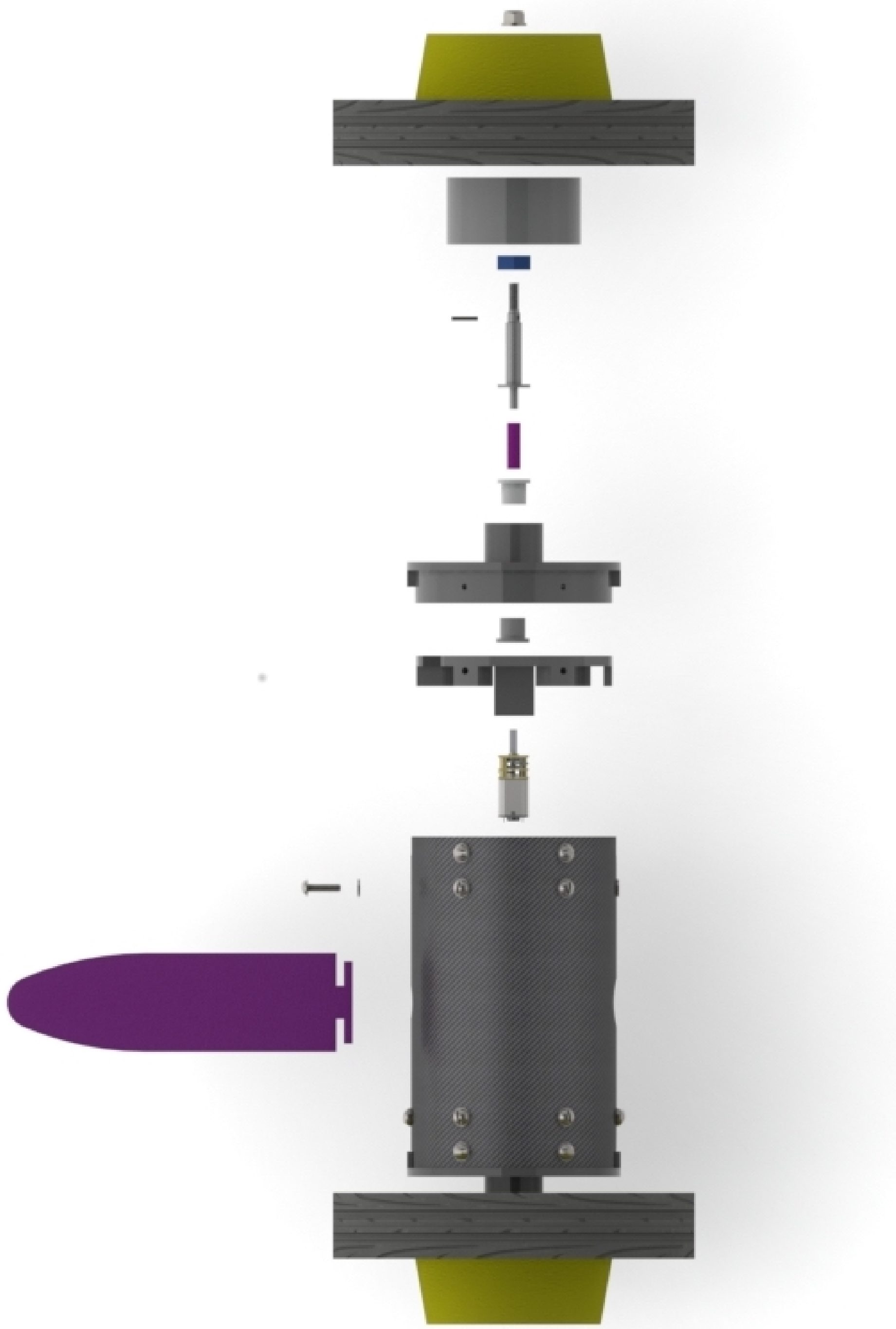


Figure E3: Mk2 Prototype Exploded Drive Train

E.2 Bill of Materials

Section	Component	Material	Mass (g)	Quantity	Mass Total (g)	Cost ($)	Vendor
Chassis	Suspension Walls	Nylon	36.4	2	72.8	0.35	McMaster
	Sleeve Bearing 0.375" OD; 0.25" ID; 0.125" long	Plastic	1	4	4	16.00	OilLite
	Socket Head Screw 6-32 Thread Size, .5" Long	Stainless Steel	1	20	20	0.26	Grainger
	6-32 Lock Washers	Stainless Steel	0.2	20	4	0.50	McMaster
	Chassis Body	Carbon Fiber	61.3	1	61.3	28.00	DragonPlate
	Inner Wall	Nylon 6	35.2	2	70.4	0.17	McMaster
	Support Bars	Carbon Fiber	2.5	3	7.5	6.38	DragonPlate
	Padding	Neoprene	2.3	1	2.3	0.36	Amazon
	Tail	PMC-790	13.5	1	13.5	0.35	Reynold's Advanced Materials
	Camera Holder	Nylon 6	11.9	1	11.9	0.06	McMaster
Wheels and Shafts	M4mmx0.7 Lock Nuts	Steel	1.3	2	2.6	0.16	McMaster
	.25" OD Drive Shaft	Steel	8.8	2	17.6	3.62	McMaster
	Hubs	ABS Plastic	11	2	22	15.00	Tamiya
	Steel Pin	Steel	0	2	0	0.03	Tamiya
	Plastic Hex Insert	ABS Plastic	0	2	0	0.03	Tamiya
	Tubing	Silicon	0.1	2	0.2	1.39	McMaster
	Poron Wheels	Poron	71	2	142	30.00	Rogers Corporation
	Poron Wheels	PlastiDip	0.04	2	0.08	0.00	United States Plastic Corporation
Electronics	Pololu 30:1 Micro Metal Gearmotor MP 6V		9.467	2	18.934	15.59	Pololu
	Lithium Ion Battery		40	1	40	20.00	All-battery
	FPV Combo 3-In-1 600TVL Mini Camera 5.8GHz 40CH 25mW Wireless Transmitter		5	1	5	29.17	Range Video
	mbed LPC1768 Microcontroller		7	1	7	54.95	SparkFun
	Sabertooth Dual 5A Motor Driver		15	1	15	59.99	Dimension Engineering
	900 MHz Xbee Radio		7	1	7	39.99	Master Electronics
	Perfboard		10	1	10	5.00	Amazon
Dropper	Deployment Payload	From PSI	97.88	1	97.88	--	--
*Masses marked as 0 weigh less than 0.01 g				Mass Total:	652.99	327.35	

F Documentation for Manufacture and Design

Assembly Procedure

ENGS 89/90, Group 1: AIMGRO
March 3, 2017

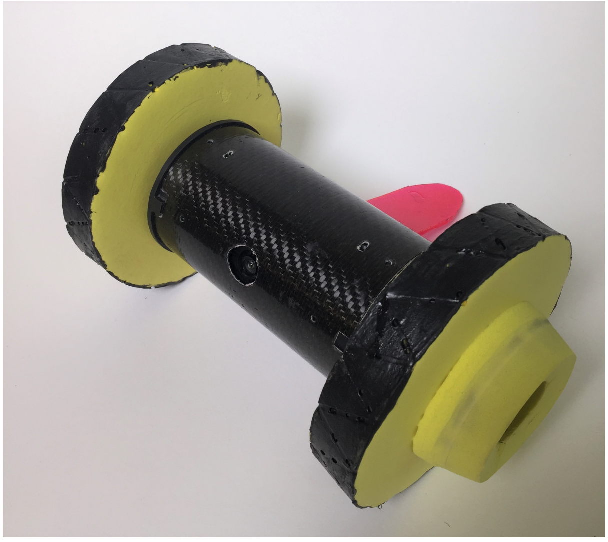


Figure 1: Full AIMGRO assembly

1 Inner Chassis

1.1 Cross Bars + Camera Wall

Glue the ends of the three carbon rods into the two plates of the inner chassis along with the camera wall. Make sure the camera wall is facing outward. Allow the glue to cure entirely before proceeding. Epoxy or SuperGlue is recommended.

1.2 Electronics

*Note: Some photos are from the AIMGRO Mobility vehicle (Mk1) and are slightly different from the MK2 make up. The overall process is the same.

These steps assume the electronics are wired and ”pre-assembled” as described in the last section of *Electronics Documentation*. Prior to inserting electronics, make sure to line the chassis wall with preferred damping material. (Recommended: Sorbothane)

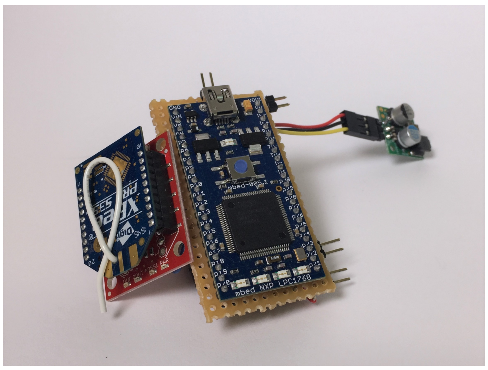


Figure 2: Properly configured electronics

Step 1: Motors + Motor Controller

Connect each motor to a pair of motor outputs (M1A/M1B, M2A/M2B). The red leads should be in M1A and M2A. The black leads should go in M1B and M2B. Place the motor controller in the bottom of the chassis horizontally so that it fits lengthwise. Insert the motors into the housing on each side of the chassis with the red leads closer to the camera. Press the motors into the housing until the front wall of the gear box touches the inside wall of the chassis.

Step 2: Camera

Insert the camera into the camera slot in the wall of the chassis. The antenna will protrude above the wall holding the camera. It is meant to be a tight fit; slowly press the camera into the spot until the lens is up against the circular opening in the outside of the chassis wall. Adjust the soft antenna however necessary to make sure the camera is fully inserted into the housing and out of the way of the open space in the chassis. If necessary apply a small amount of super glue to hold the camera in place.

Step 3: MCU + Radio + Voltage Regulator

Once the Sabertooth motor controller is in place, connect it to power and ground. Connect S1 and S2 to microcontroller pins 23 and 24 respectively. This should supply 7.4V to the Sabertooth 2x5. Place the LPC1768 (already wired to the radio and voltage regulator) inside of the plastic chassis. The radio should be on the opposite side of the chassis from the camera with the microcontroller sitting on top. The voltage regulator can be adjusted to take up any extra space above or below the motors. Connect the camera to power and ground. (Nothing should be powered at this time, the battery should still be disconnected from the system).

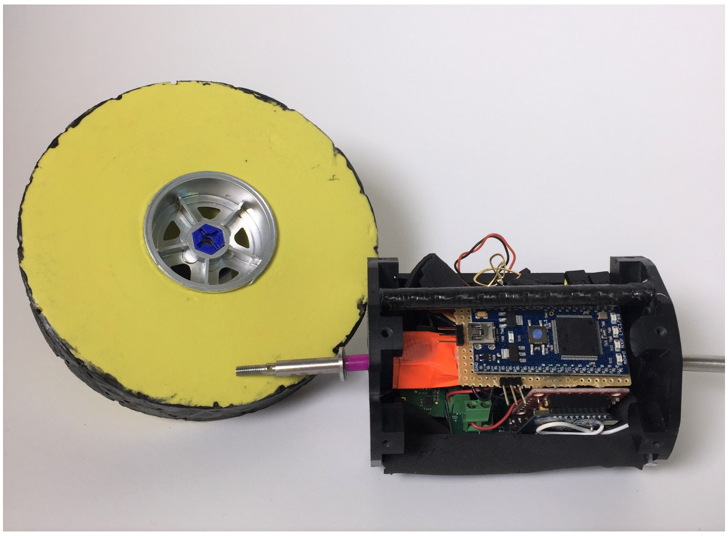


Figure 3: Properly assembled electronics (without battery)

2 Battery

Place the battery in the chassis directly on top of the LPC1768 so that the top of the battery is below the circular profile of the plastic inner walls of the chassis. Place additional damping material on top to enclose the electronics.

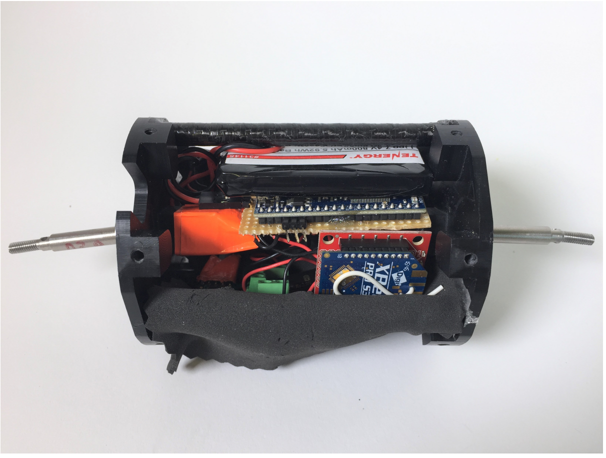


Figure 4: Properly assembled electronics (with battery)

3 Drive Train

3.1 Tubing

Slide one end of the tubing onto the motor shaft and glue in place using epoxy. Slide the other end of the tubing onto the smooth end of the drive shaft (no threads) and glue in place. Excessive glue is unnecessary; it only acts to protect against the tubing coming off the shaft during impact. Do this for both drive shafts, on both sides of the inner chassis.

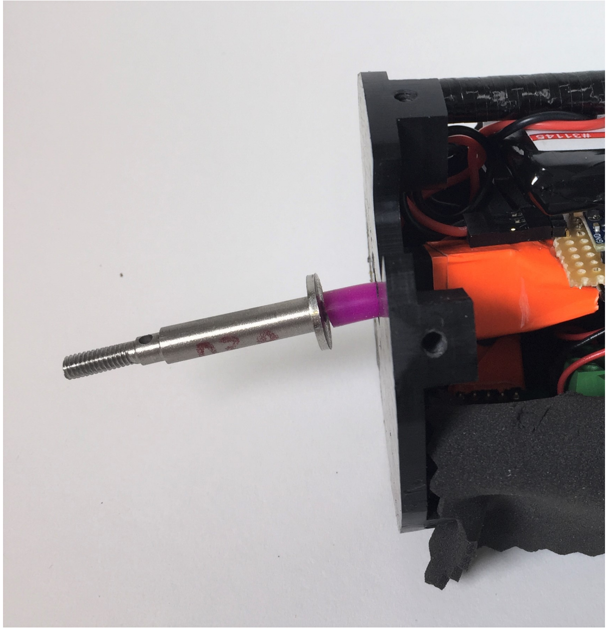


Figure 5: Drive train assembled with tubing

4 Outer Chassis

4.1 Main Body

Insert the inner chassis (drive shafts attached) into the carbon shell. If you use a switch, you will have to line up the notch in the wall with the switch poking through the carbon shell. Once the notched wall of the chassis slides past the switch make sure to rotate it so that the camera holes line up. Fasten the inner chassis in place using the steel screws through the holes in the carbon. Make sure to use the rubber washers between the screw head and the carbon surface.

Figure 6: Sliding the inner chassis into the carbon tube

4.2 End Plates

Slide the nylon plates over the drive shafts and press into the sides of the carbon chassis. The press fit is meant to be very tight and the tabs on either side of the nylon plates will press into the tab-shaped openings at either end of the carbon tube. Set in place using the same steel screws. Make sure to use rubber washers.

Figure 7: Two side plates, a.k.a. ”Suspension Walls”

Figure 8: Chassis assembled with fasteners in place

5 Wheels

Slide the tiny metal pins through the hole in each drive shaft. Place the blue plastic, hexagonal cap over the end of the drive shafts and pop it onto the pins. Attach the wheels by matching the blue hexagon with the hexagonal pocket on the inside of the wheel hubs. Screw the lock nut onto the end of the drive shaft (on the outside of the wheel) using the cross-shaped piece. Repeat for the second wheel. Make sure to tighten the lock nuts all the way.

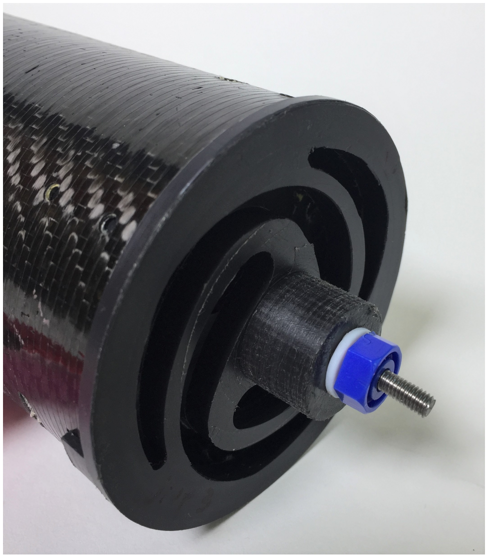


Figure 9: Drive shaft with hex piece for wheel attachment

Figure 10: Inner face of wheel hub with hexagonal attachment piece

6 Operation

To operate the robot connect the second radio to the second LPC1768 and connect the microcontroller to a serial port on a computer. Use pins 13 and 14 on the micro for radio tx,rx. Once the serial port is open the radio can start sending drive commands to the robot (assuming the ground robot is on). The only drive commands are forward/back (R/C), left/right (D/F), and stop (S). The more times you hit the commands the faster the robot will go until the controller reaches the maximum magnitude voltage for the motor outputs. To attach the AIMGRO robot to the InstantEye air vehicle slide the servo pins on the dropper attachment through the tabs on the top of the carbon shell.

Electronics Documentation

ENGS 89/90, Group 1: AIMGRO

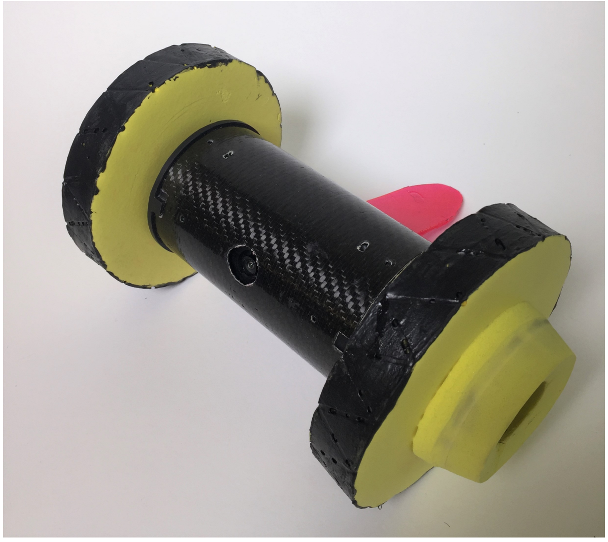


Figure 1: Full AIMGRO assembly

1 MBed LPC1768 + Accessories

The LPC1768 Microcontroller can be operated with 4.5-9V. It is recommended in this case to use 5V for the microcontroller in order to minimize power consumption. The XBee radio will be operated with the 3.3V regulated output on the microcontroller.

1.1 Pin Configuration

The communication between the radio and the mbed uses pins 13 and 14 on the microcontroller for serial tx,rx. The pwm outputs are on pins 23 and 24 and wire to S1 and S2 on the Sabertooth 2x5 motor controller.

1.2 Programming

First program the microcontroller that on the AIMGRO ground vehicle. Compile main.c in the AimgroVehicle program and drag and drop the file onto the mbed icon in the Finder window. For the second mbed compile main.c in the AimgroControl program and upload it to the microcontroller.

1.3 Voltage Regulator

The voltage regulator operates on any voltage up to 38V and reduces it to 5V. The battery is 7.4V. Connect the power and ground from the battery to the Vin and GND on the voltage regulator. Wire the battery ground/regulator ground to GND on the LPC1768. Connect Vout (5v) from the regulator to Vin of the LPC1768. It is recommended to do this with a pin connector so that the voltage regulator can be easily removed or replaced.

1.4 XBee Radio

Before wiring the radio make sure to configure with the proper settings. To do this use the SparkFun USB Explorer breakout board to connect the radio to a computer. Use XCTU to open the radio settings and set the bit rate to 115,200 bps.

The XBee radio operates on the 3.3V regulated output from the top right pin on the microcontroller. Make sure to properly wire it to either the 3.3V input pin on the SparkFun breakout board (no USB). Wire the system ground to one of the radio GND pins.

Lastly, wire DOut and DIn on the XBee breakout board to p13 and p14 respectively on the LPC1768.

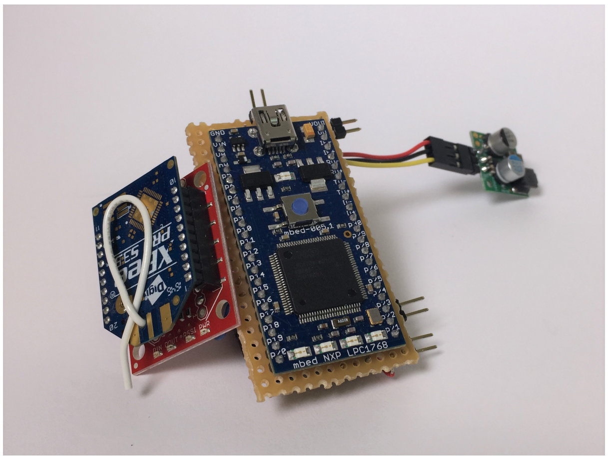


Figure 2: Properly configured electronics

2 Sabertooth 2x5

For the AIMGRO robot to operate as described by this manual it must be in linear mixed mode. To do this flip switches 1 and 6 down while keeping switches 2-5 up. Plan on connecting wires to the motor controller using the built in clamps which are tightened with a small flathead screwdriver.

B+ and B- on the Sabertooth are connected directly to battery power and ground respectively via the perf board or breadboard holding the microcontroller. S1 and S2 are wired to p23 and p24 respectively on the LPC1768.

2.1 Motors

The red and black wires should be soldered to the motor terminals. When connecting the motors to the motor controller (in the assembly process), clamp the red wires in M1A and M2A. Clamp the black wires in M1B and M2B. Do not do this until you are actually assembling the inner chassis for use.

3 Analog Video

The camera operates off of 2.5-5V and should be connected to the system ground and the step-down regulator output or the 3.3V pin on the microcontroller. The analog video receiver can be powered on and will show the video stream on the screen. If the video stream does not appear after boot-up change the channel until it does.

4 Finished Product

For instructions on how to place the electronics into the AIMGRO chasis please see the **Assembly Procedure** document.

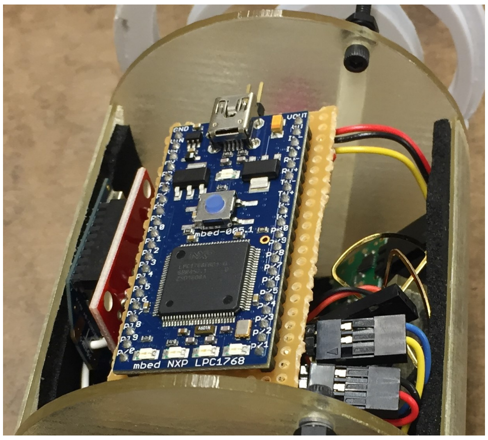


Figure 3: Properly assembled electronics in the chassis (without battery) in Mk1

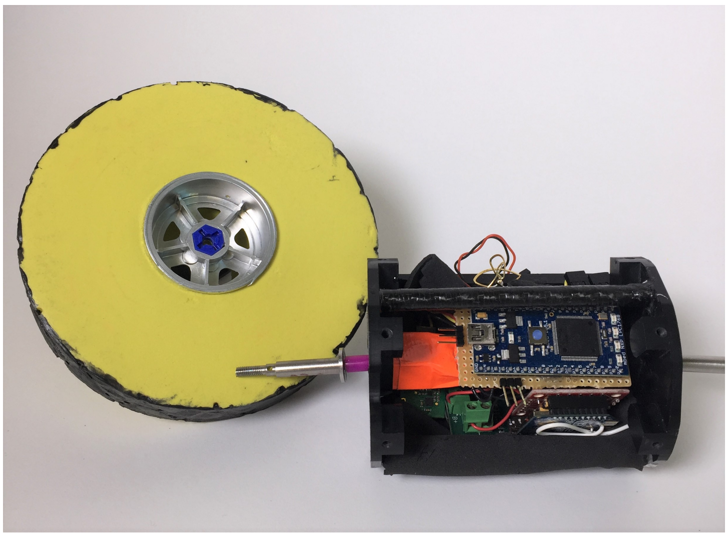
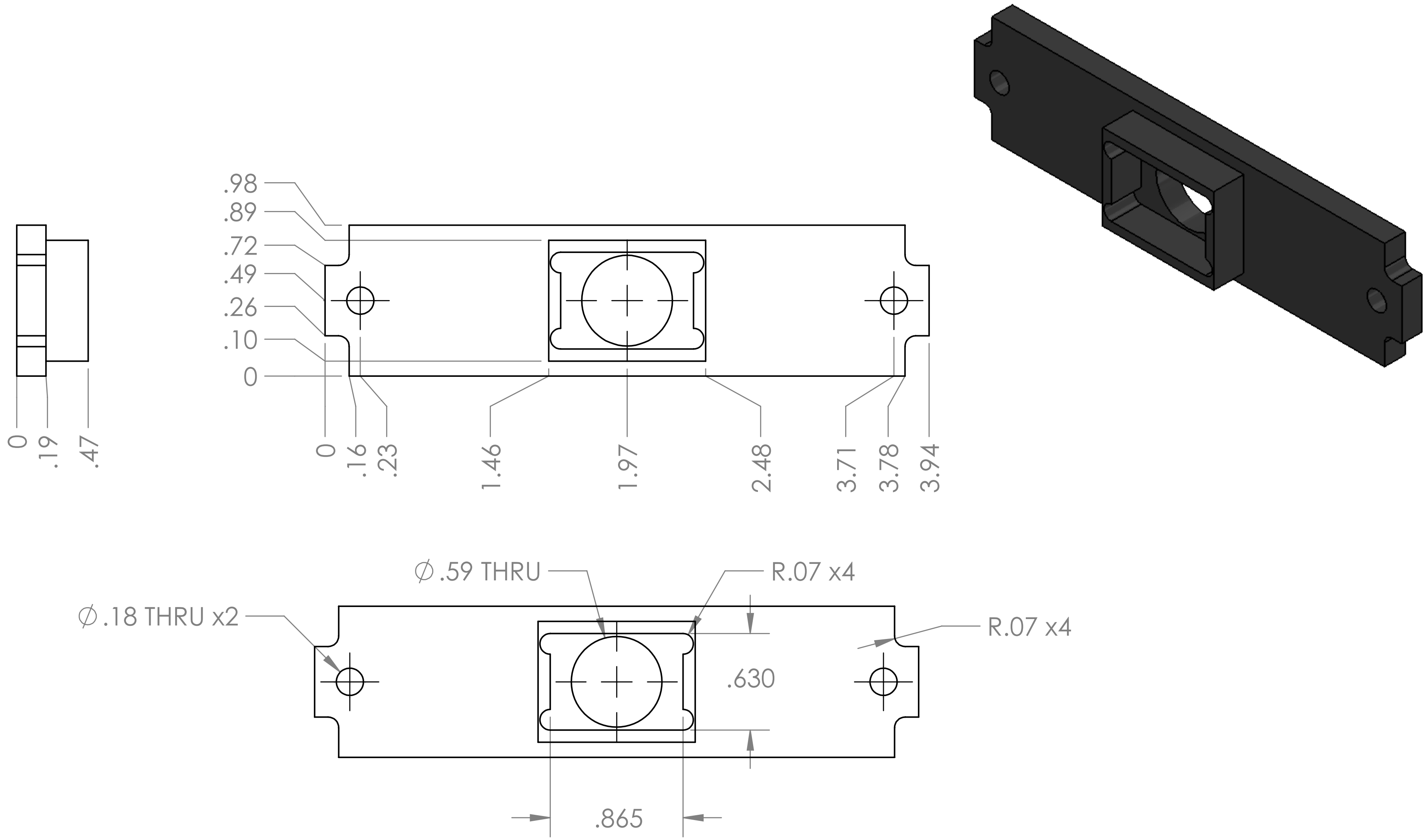


Figure 4: Properly assembled electronics (without battery) in Mk2



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	CHECKED	PJL	03/02/17	
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL Nylon	COMMENTS:			SIZE A — DWG. NO. Camera Wall — REV
FINISH As Machined				
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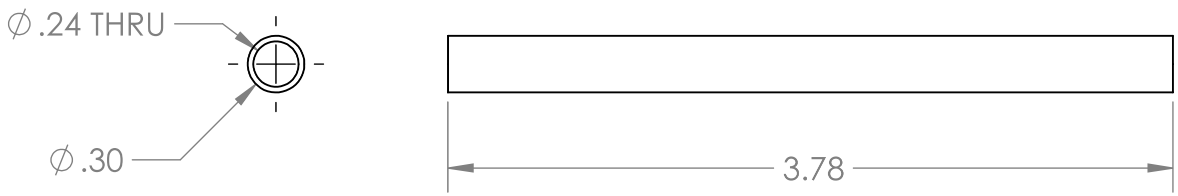

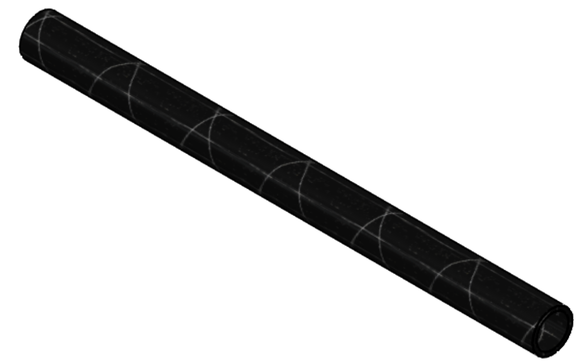

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	CHECKED	PJL	03/02/17	
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	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL Carbon Fiber	COMMENTS:			SIZE: A — DWG. NO.: Carbon Tube — REV
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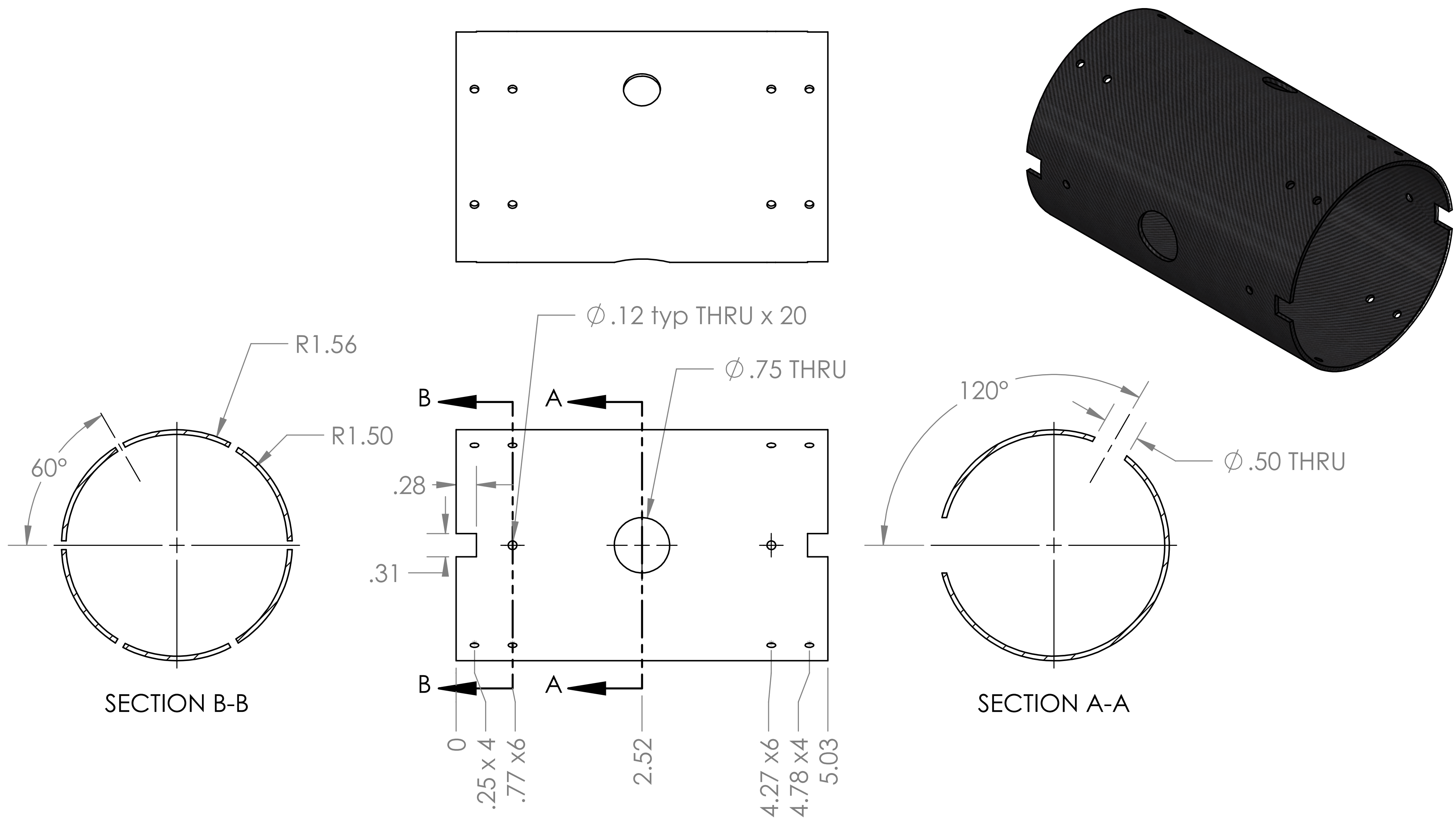

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	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL Carbon Fiber	COMMENTS:		
FINISH As Machined			
DO NOT SCALE DRAWING			

TITLE: ENGS 90 Group 1: AIMGRO

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

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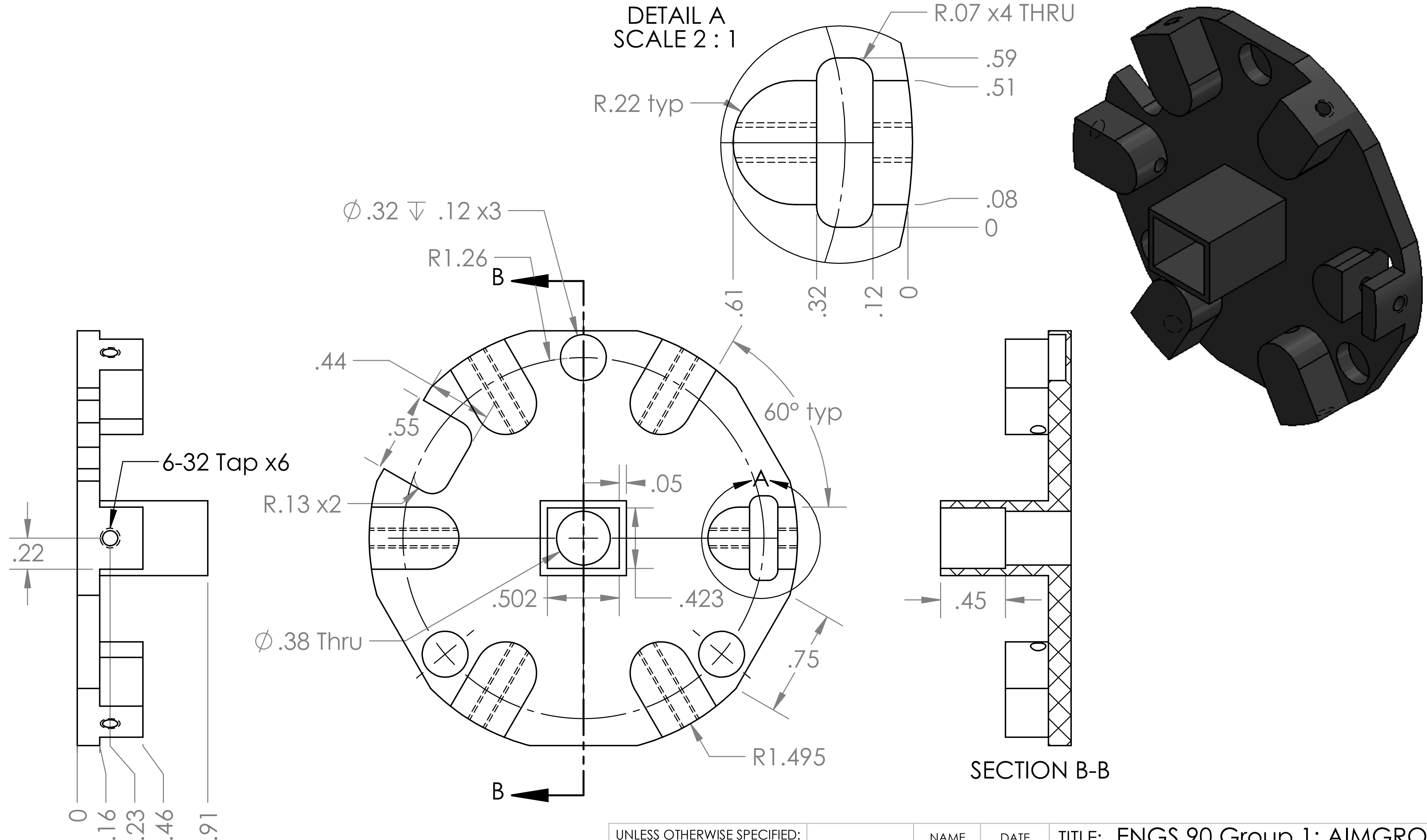
A	Chassis Tube	
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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	CHECKED	PJL	03/01/17	
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL Nylon	COMMENTS: GCD Machine Code Provided			SIZE A — DWG. NO. Left Inner Wall — REV
FINISH As Machined				
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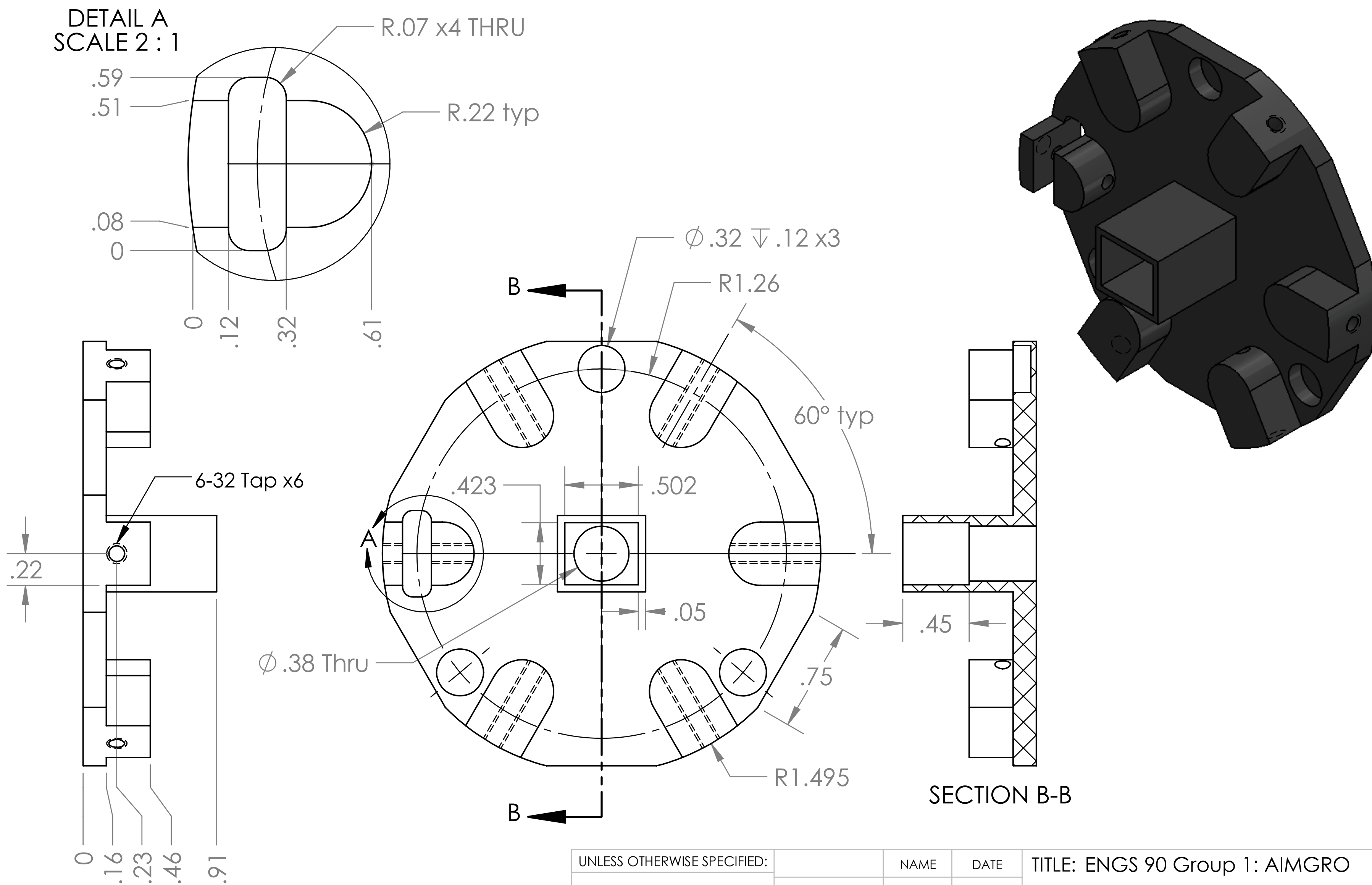
5 4 3 2 1



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	CHECKED	PJL	03/02/17	
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL Nylon	COMMENTS: GCD Machine Code Provided			SIZE A — DWG. NO. Right Inner Wall — REV
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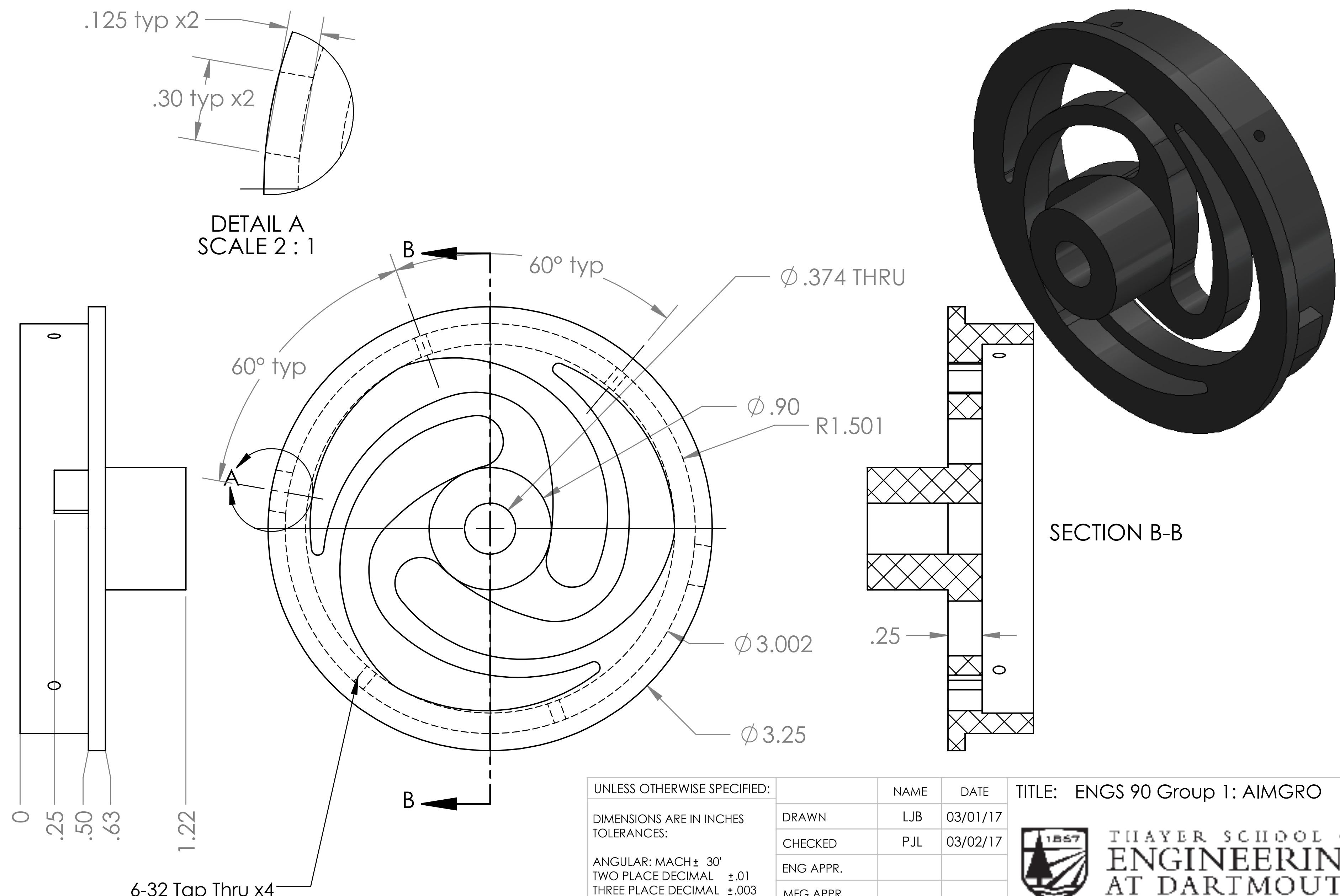

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	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL Nylon	COMMENTS: Additional DXF file for dimenisions of inner spiral pattern. G code for machining provided as well.			SIZE A · DWG. NO. Suspension Wall · REV
FINISH As Machined				
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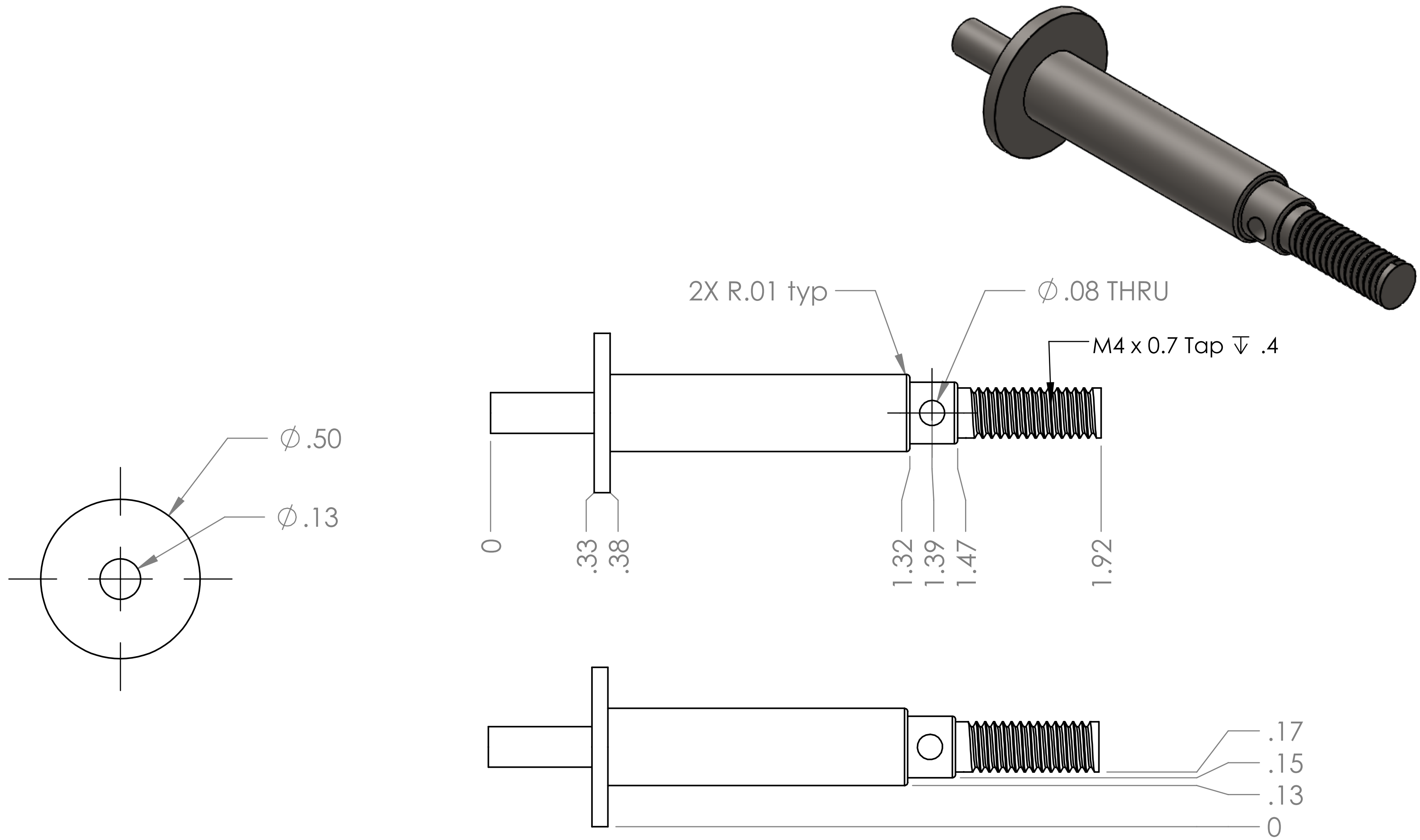

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	MFG APPR.		
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MATERIAL Steel	COMMENTS:		
FINISH As Machined			
DO NOT SCALE DRAWING			

TITLE: ENGS 90 Group 1: AIMGRO

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

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A	Drive Shaft	
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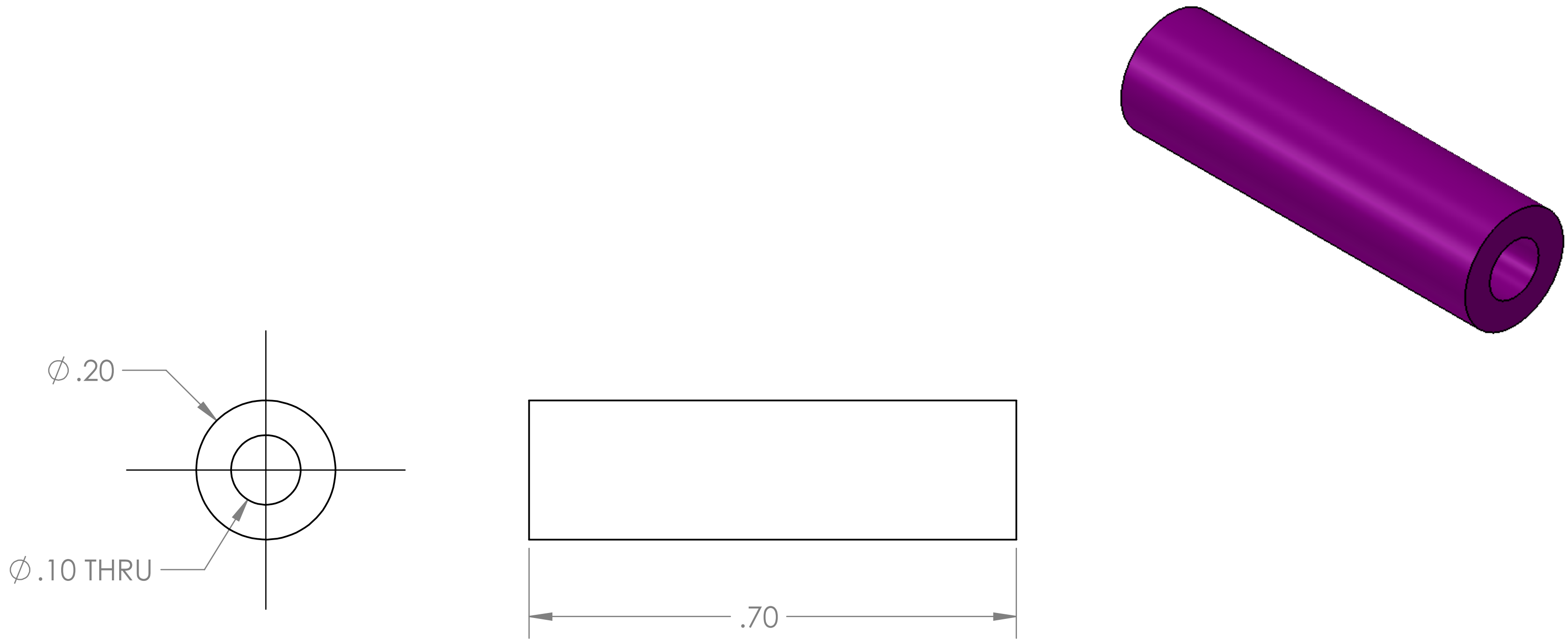
5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
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	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL Soft Plastic	COMMENTS:		
FINISH As Machined			
DO NOT SCALE DRAWING			

TITLE: ENGS 90 Group 1: AIMGRO

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

SIZE	DWG. NO.	REV
A	Tubing	

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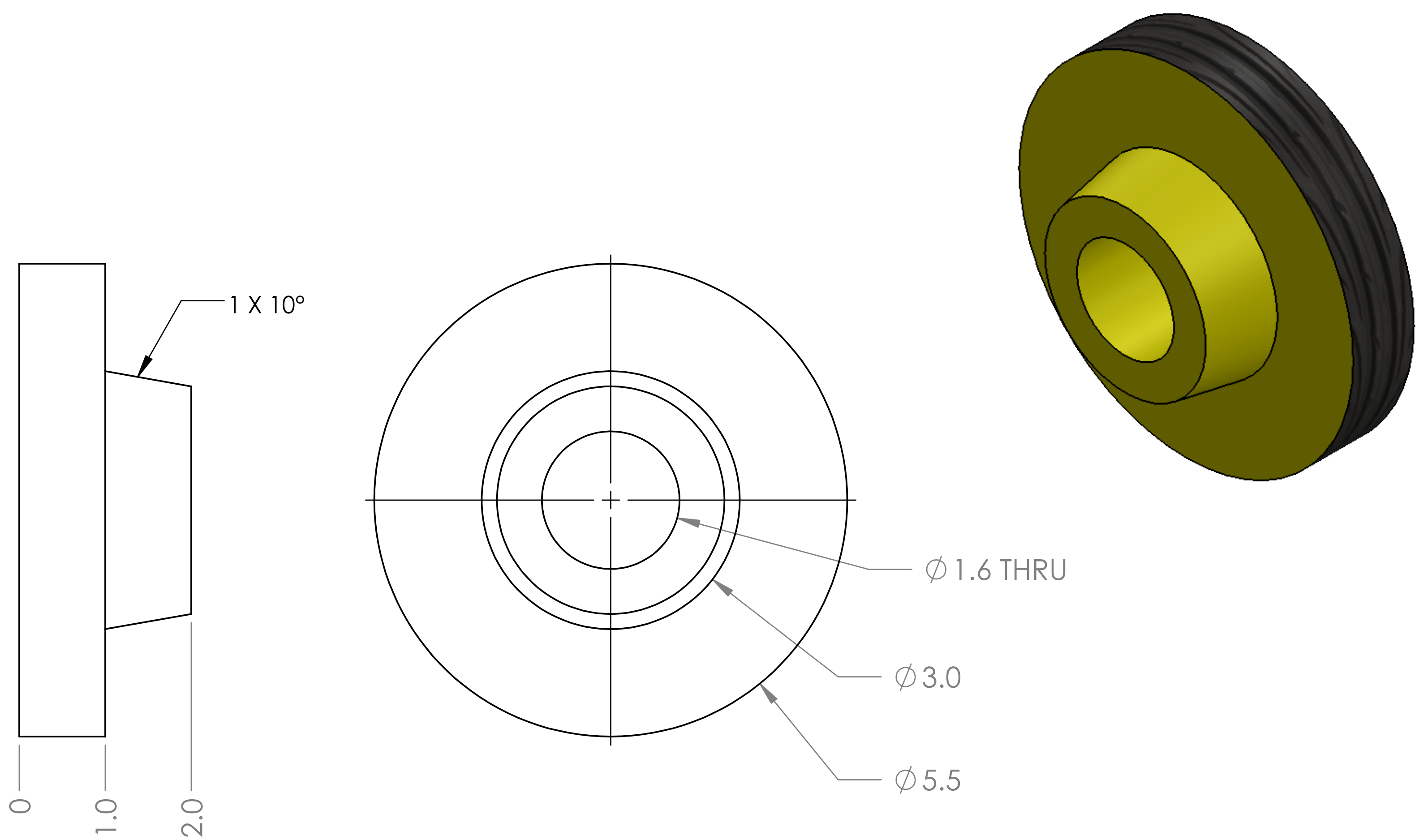

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	CHECKED	PJL	03/01/17	
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL PORON XRD	COMMENTS:			SIZE A — DWG. NO. Poron Wheel — REV
FINISH Rubber coating on OD				
DO NOT SCALE DRAWING				SCALE: 1 : 2 — WEIGHT: — SHEET 1 OF 1