Computer Controlled Aiming & Tagging System

Final Design Report

EML 4551C – Senior Design – Fall 2011 Deliverable 1

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Executive Summary

The Air Force Research Lab at Eglin is researching the accuracy and reliability of their fuze sensors. These sensors are used in Eglin's missile guidance systems to locate and lock on to possible targets. The munitions directorate needs a system to test the ability, accuracy and launch algorithms of the fuze sensor systems.

This project deals with creating a Computer Controlled Aiming and Tagging System, or C-CATS, which will test Eglin's fuze sensors. This system needs to be a non-destructive missile tagging system that will mark the center of the would-be impact and explosion on the target. Eventually, the C-CATS will be mounted to the front of the fuze sensors system and act as a scaled down warhead. The fuze sensors will constantly be updating the C-CATS with location coordinates, and when the sensors decide it is time, the C-CATS will be told to fire a marker, which is the "non-destructive" replacement of a full scale warhead. This will allow Eglin to see real time results for their future targeting system without damaging any components.

The mechanical system will only be tested statically for fire latency, shot accuracy and shot dispersion. Since no system like this exists, Eglin wants to make sure the system is accurate and stable enough in a static testing environment before dynamic testing occurs. Therefore, the C-CATS will only be tested and analyzed from a stationary firing position, leaving the dynamic testing to future teams. The system needs to be tested to be within specifications because it will eventually be testing accuracy and ability of the full fuze sensor system.

In order for Eglin to get the most accurate results for their tests, there are restraints that must be adhered to so the system will be up to standards. The most important constraint is that the marking system can traverse the entire forward hemisphere of the warhead to mimic the same ability of the real missile. It also must be able to turn the 360 degree azimuth in under 1 second. This is a feature designed for the future dynamic testing so the C-CATS program would have enough time to locate a target and position the aiming system before impact. The resolution of the motors must also be less than 1 degree so the motion of the marker is as smooth as possible. Another restraint is that the system must be less than 50 pounds because the rigging system has a weight limit, so the system cannot exceed that limit or it cannot be tested. The last major constraint is the system will be controlled by user input and must be safe to fire and will not have any unwanted discharges.

The system will be statically tested, firing at targets at a range of 25 meters, using manual user inputs as its targeting system. The manual input will act in place the RF and optical sensors, as they give only directional outputs, therefore our system should easily take commands from them in the future, when the programming language is compatible.

Project Overview

Need Assessment

As the advancement of image fuze sensors progress, a nondestructive method is needed to evaluate the performance of the fuzing sensors at the endgame of flight to ensure peak performance and reliability. This project will require the use of nondestructive test methods in order to evaluate the accuracy of the fuze burst point control algorithm during each simulated flight using static testing methods. In addition, the speed and accuracy of the tagging system should be compatible with continuous target updates as the fuze sensor closes on the target and refines the burst point decision.

Project Scope

Problem Statement

To design and fabricate a nondestructive computer controlled aiming and tagging system. The system will use a barrel that will mount on the front of the surrogate warhead and cover the entire forward hemisphere and leave a ballistic marking for data collection. Our system will serve as a proof-of-principle demonstration at the Air Force Research Laboratory for future implementation of fuze sensors on munitions.

Justification/Background

The Air Force Research Laboratory (AFRL) needs a method to evaluate performance of fuze sensors and algorithms in a dynamic field test environment. The fuze sensors are designed to image the forward hemisphere in front of a weapon's velocity vector for the last 100 meters of flight, detect targets of interest, classify these targets and pick an aimpoint on the target. For proof-of-principle demonstrations, AFRL plans to eventually use a dynamic cable test rig that will allow the fuze sensor to fly a realistic trajectory toward the ground at scaled velocities. Figure 1 shows the testing rig with the height and angle used during testing.

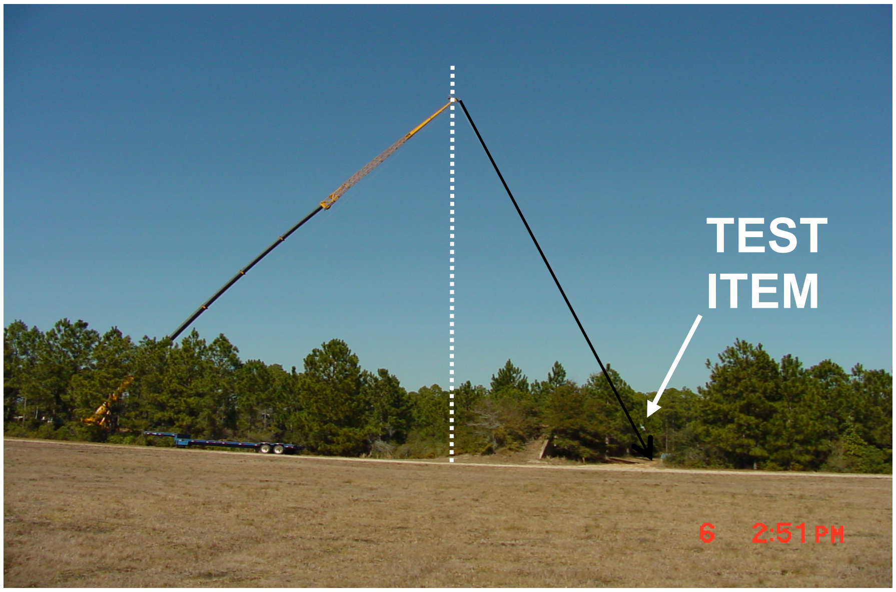


Figure 1: Eglin's Dynamic Testing Rig Configuration

In the past, cameras and sensors have been used to pin point the accuracy and direction of the fuze sensors during each cable run. This is an accurate method, but calls for hours of post-processing, from downloading the data collected, to analyzing it to determine whether or not it was a good run. If it was a bad test, or tests, then the whole process must start over, starting at setting back up the cable system, and then running multiple tests, and finally back to more post-processing. So, the AFRL is looking for a reliable way to gather real time data feedback in the on field tests. This instant feedback will allow for immediate analysis on the accuracy and direction of their fuze sensors.

Objective

Design, fabricate, and demonstrate a computer controlled aiming and tagging system that can eventually be integrated with developmental active imaging fuze sensors for proof-of-principle demonstrations. For this prototype, targets of interest will be placed at respective realistic distances from the weapons trajectory to evaluate the effectiveness of the active imaging fuze sensors in a static data collection environment. A paintball gun like system is needed that can be aimed and fired by the fuze sensor during these initial static test simulations. The prototype must be able to receive a user defined set of coordinates, move the barrel to the target and accurately fire several paintballs to tag the target. It must do this with a high level of precision and accuracy and at a defined speed.

Safety

Because this design is a live firing system, there will need to be safety precautions implemented to make sure the device only fires when commanded to do so. The most important and easiest way to guard against unexpected firing is to have a safety key that, when removed, the system is unable to fire at all. This interrupt can be a physical or electrical interrupt depending on our final design and which one is determined to work the best.

Another safety precaution that will be taken to prevent any unwanted discharges is that our device will have an external trigger input. This will be a separate and secure input system that is only used to tell the system when to fire. The device will have a completely separate input system that controls the azimuth and elevation of the firing device. This precaution is to prevent any bad information being sent to the trigger while the aiming system is still aligning itself. These are going to be the main two ways of preventing the system from firing unexpectedly.

Expected Results

By the end of the senior design project, our goal is to have a fully functional, nondestructive marking device that will allow AFRL to test the accuracy and repeatability of their computer controlled aiming and tagging system. The product will have the capability of computer interfacing to allow even more testing capabilities for the Munitions Directorate. The final product will be lightweight enough to carry the necessary control systems and have some sort of marking system that will be able to range the entire forward hemisphere of the device. The product, fully functional, will be within the given safety standards and will be able to fire multiple marks with accuracy and be able to repeat all tests.

Product Specifications

After multiple conference calls with the sponsor, the customer needs were determined, which have been outlined in the project scope. Table 1 shows the high level engineering specifications that were agreed upon by the group and the sponsor that correspond with the customer needs.

Table 1: High Level Specifications

Specification	Value
Budget	$2000
Maximum Range	25 m
Azimuth Range	360°
Elevation Range	90°
Angular Velocity	≥ 360°/s
Resolution	≤ 1°/s
Maximum Weight	50 lbs.
Power Source	Honda EU1000i Generator
Motors	Servos
Tagging System	Paintballs

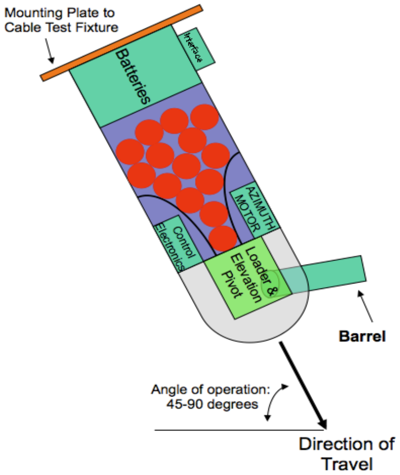


Figure 2: Early Component Mock Up

Along with the product specifications, the customer provided us with a simple mock up of the general components that will be necessary to complete this project. Figure 2 shows the drawing with the parts. Its to be noted that there are a couple of components present in this figure that will not be necessary in the final design due to the fact that we are designing for a static test only. One is the mounting plate, which would be present to mount the system to the test rig that we will not be using, so it is not necessary. Also, it shows the angle of attack as 45° to 90° below the horizontal, which is not a necessary design parameter for the static testing. It should also be noted that since this mock up list was sent, the power source has been changed. Instead of batteries, which must be recharged frequently, a Honda generator will be used in its place, which will be provided by the customer.

Concept Generation

Concept 1

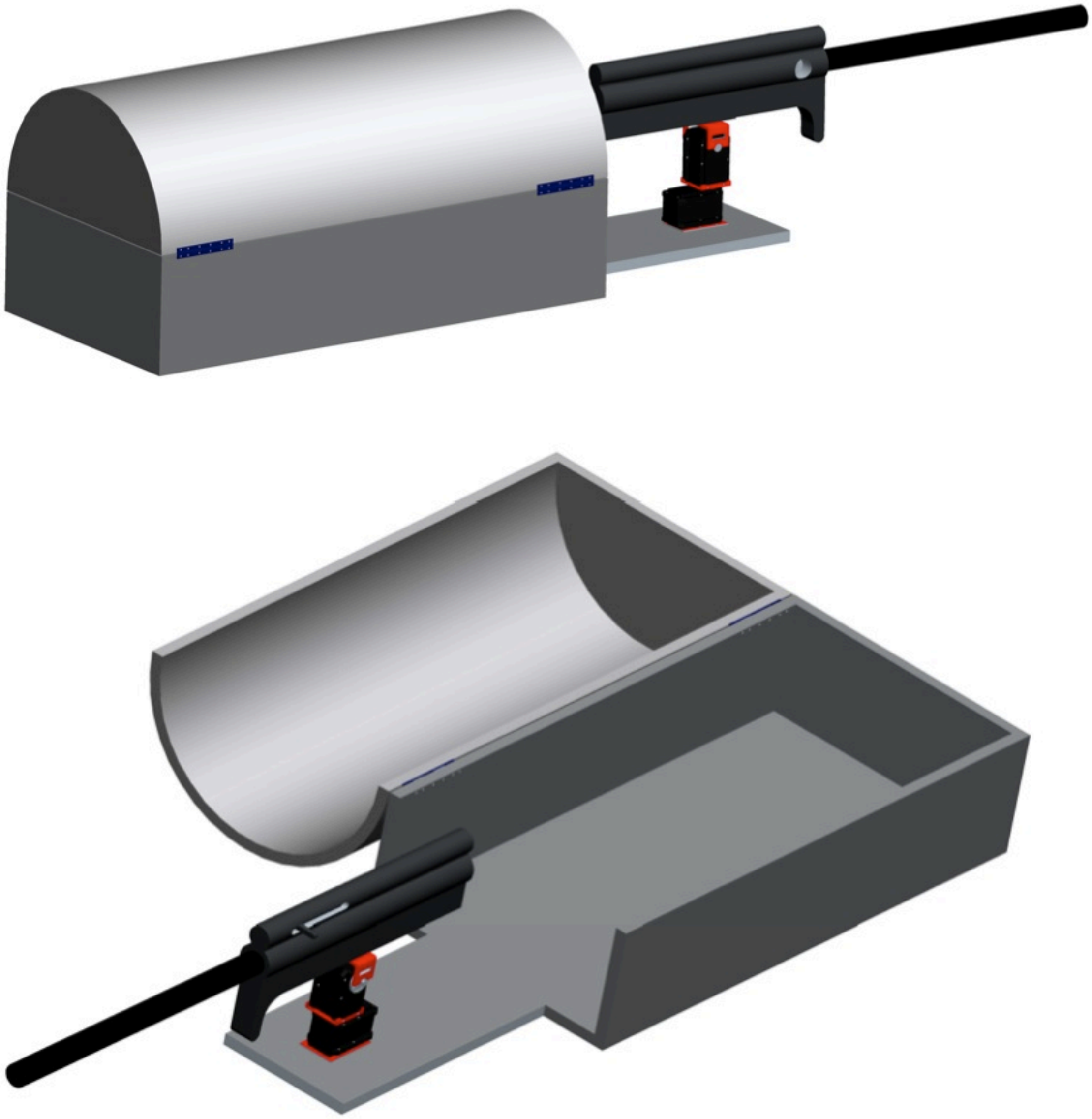


Figure 3: Concept 1 CAD Drawings

Concept 1 is based on the idea of a compact, aerodynamic, stationary shell or housing, with the gun and both motors exposed and rotating on their own. Figure 3 shows a picture of the concept. None of the components are shown, but they will all be housed in the back "mailbox" shaped portion of shell. The top of the shell is hinged which would allow for easy access to the components if anything needed to be adjusted.

Table 2: Concept 1

Concept 1 Properties:	
Housing	Aluminum 2024/6061
Elevation Torque Needed	4.95 N*m
Azimuth Torque Needed	5.59 N*m
System Weight	49 lbs.

Pros

The pros of this system is that the motors are sitting completely free out in the front of the assembly and is only supporting the weight of the gun. This is good for multiple reasons. For one, this allows a complete view of the forward hemisphere by the gun, with the ability to rotate in any direction without the possibility of any other components getting in the way. The other reason this design is very good is that the motors are only supporting the weight of the gun, and the gun is mounted directly to them, so there are no arms that have to be rotated, which adds torque. This improves the performance of the motors and the life of the motors.

Cons

There are some drawbacks to this type of concept. The con that is possibly the most glaring is that the system weighs almost 50 pounds. This gives no room for error when fabricating or assembling the system. Also, all of the components are locked and stationary in this design. This could cause possible bindings of wiring or hosing while the gun is moving. If anything were to lock up the air tube or the ball feeding hose, the system would be unusable. Another downside to this design is the platform the gun and motors sits on. There are not many ways to support this platform without adding more weight or size to the system, but without any support, there is no guarantee the platform will be steady enough in the long run.

Concept 2

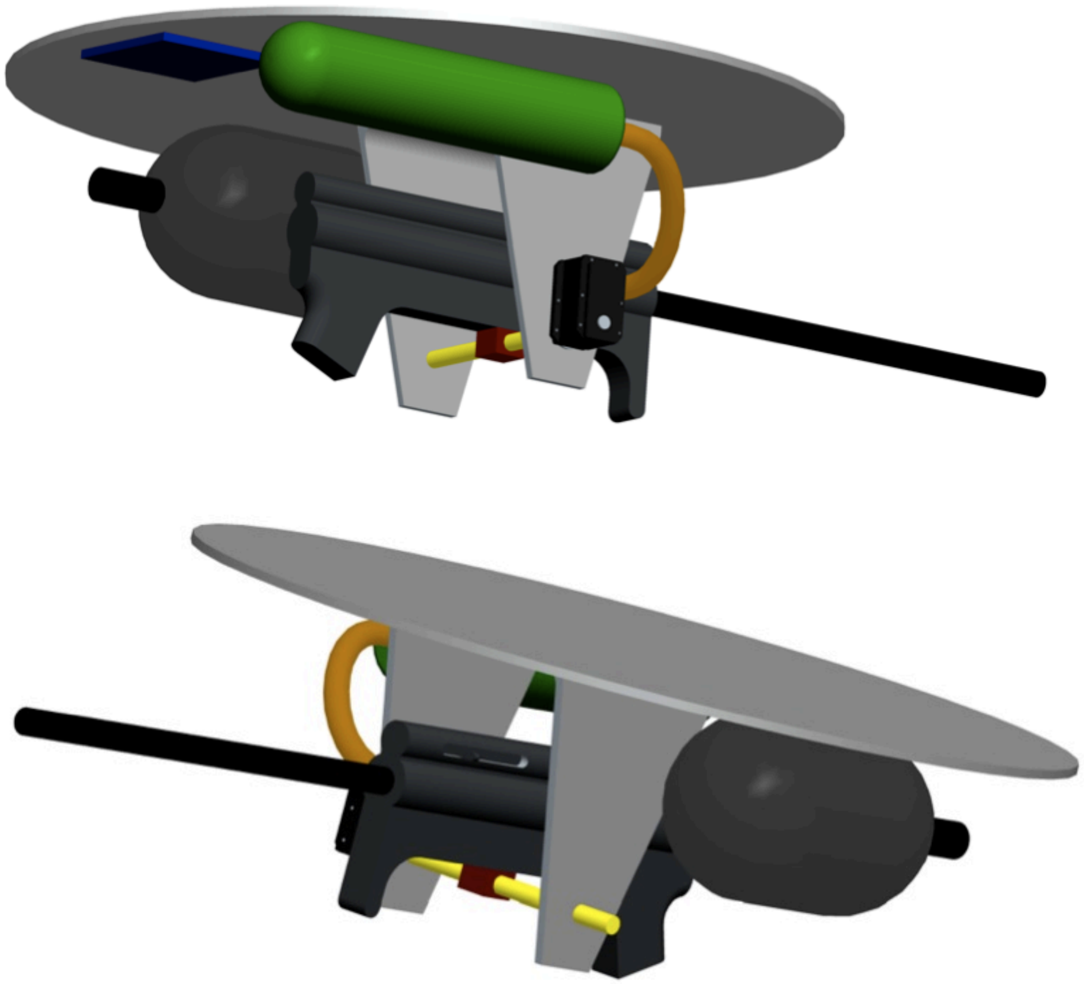


Figure 4: Concept 2 CAD Drawings

Concept 2 is based on a turret design similar to that on a B-25 Mitchell bomber. Its design is made up of a base plate that will be made of aluminum, either 2024 or 6061, due to the fact that it is light weight, but strong enough to hold the brackets where other components will be housed. Figure 4 shows this baseplate with the different components that will be mounted to it. Not shown is the motor that would be mounted to the baseplate and drive the azimuth direction of the system’s motion. Concept 2 will then have an “A” shaped bracket that will hold the actual paintball gun and the elevation motor. The rigging mounts for this concept are not shown and would be placed on the large baseplate.

Table 3: Concept 2

Concept 2 Properties:	
Baseplate	Aluminum 2024/6061
Gun Bracket	Aluminum 2024/6061
Elevation Torque	4.95 N*m
Azimuth Torque	77.8 N*m
System Weight	21 lbs.

Pros

The main pro to this concept is that every component is located on the baseplate, which is all driven by one motor. This allows the entire system to spin in a full circle without having to worry about any tying or binding of wiring or tubing. Also, since this system is upside down with the gun mounted on the bottom, this would allow for an easy transition from static testing to dynamic cable testing. This is because the gun would be facing a sharp downward angle on the dynamic testing rig, and this set up is already in that configuration. This is not a requirement, but would greatly help our sponsor in the future.

Cons

This design does have some flaws though. Both motors on this design have major weak points. The elevation motor, the one shown in the picture that directly drives the gun, is strained because it is driving the gun with a rotating arm, and this arm increases the load the motor has to move by creating a moment arm. For the motor not seen that would have to drive the azimuth motion, as shown in Table 3, the torque required to move the whole plate is very large. A motor this large would not only cost too much, but also be much larger than the space or weight allows for. Also, with no bearing system, the total weight of the turret would be on the motor, burning out the motor very fast.

Concept Decision Matrix

Table 4: Concept Decision Matrix

		Concepts			
		Concept 1		Concept 2	
Specifications	**Weight**	Rating	Score	Rating	Score
System Weight	30.0%	2	0.60	4	1.20
Elevation Torque	25.0%	4	1.00	4	1.00
Azimuth Torque	25.0%	4	1.00	1	0.25
Area for Components	20.0%	2	0.40	3	0.60
Total	100.0%		3.00		3.05

It is shown in Table 4 that both concepts score very similar criteria scores. This has led the group to believe it is possible to optimize the concepts with a third and final prototype.

Prototype

After looking at both concepts and the concept decision matrix, concepts 1 and 2 are very close in terms of pros and cons. For example, concept 1 is much better in terms of torque needed by each motor, but as far as the area needed to house the components and their wiring, concept 2 is a much better idea. Because both concepts scored very close in the decision matrix, the team came to a conclusion to design a third concept with as many optimized components from the first two concepts as possible. Shown below in Figure 5 is the final optimized prototype design.

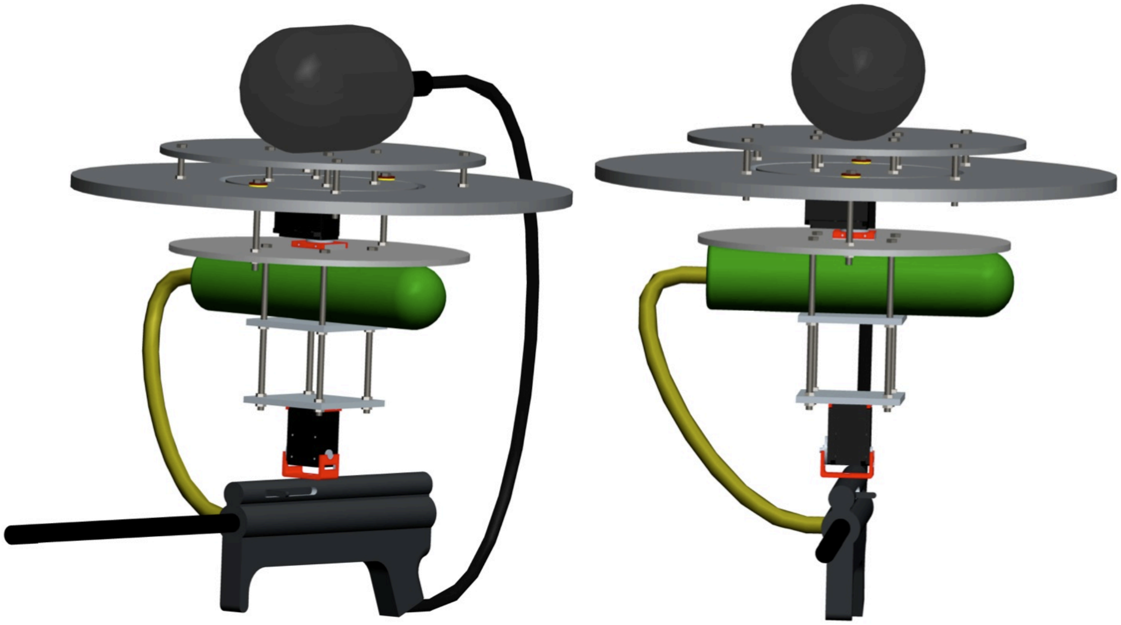


Figure 5: Optimized Prototype CAD Drawing

The first optimization was taking the motor setup from concept 1 and modifying it slightly. The elevation motor is still directly connected to the gun, which keeps its torque as low as possible. The azimuth motor is then connected in between the baseplate and the gun half. This motor is connected to the baseplate using thrust bearings, which are magnified in Figure 6**.** This is allows for a couple of things to happen. First, as shown in Figure 5, the green hopper bottle will rotate with the gun in the azimuth direction, which keeps its hose from binding, which was a downside to concept 1. Secondly, since the azimuth motor is only rotating the gun and the hopper and both objects are positioned directly above the motor, the torque needed is much less than in concept 2, which is shown in Table 5.

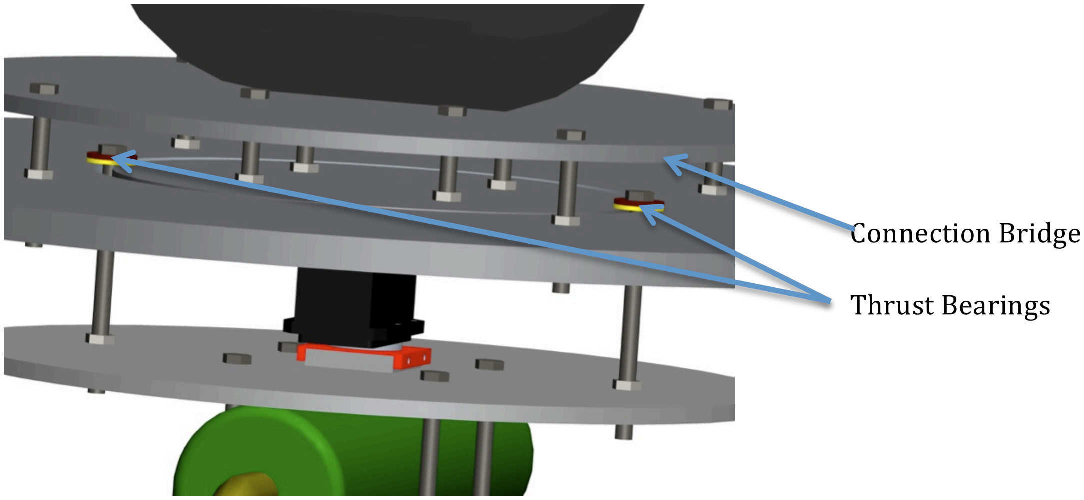


Figure 6: Zoom on Prototype Thrust Bearings and Bridge

Table 5: Prototype

Prototype Properties:	
Baseplates	Aluminum 6061
Bridge Plate	Aluminum 6061
Elevation Torque	4.95 N*m
Azimuth Torque	10.21 N*m
System Weight	30 lbs.

This design is the best of both worlds because it unbinds all the components unlike concept 1, but it still keeps as much weight and torque off of the motors unlike concept 2. It also maintains a full view of the forward hemisphere, which is one of the most important design specifications, and is under the weight limit as well.

Prototype Finite Element Analysis

Because this system is going to be supported by the large baseplate, the thrust bearings will be supporting a lot of weight, and we need to make sure the dimensions and materials being used will support this design without deforming. Using Pro/ENGINEER to determine the weight of all the components supported by the baseplate, and using Newton's second law of physics, the force supported by the bearings can be calculated. Equation 1 shows the final calculation.

$$\boldsymbol{F = m * a = 44.5\, N} \quad \text{Equation 1}$$

This force is supported by two bearings, so the force on each bearing is half of that, or 22.25 N. The boundary conditions for this plate are straightforward. The outer rim of the large plate is a fixed boundary, because it is where the system will be supported or held, so it will not move. Also, all the interior holes where the nuts and bolts fasten are considered fixed boundaries. This is because once the system is put together, the plate will not move at those points due to the nuts holding them in place. As far as initial conditions, this system is a relatively static system. Even if it eventually runs on the dynamic testing wire, this C-CAT system is not moving relative to itself. The only moving part is the gun, which is not directly connected to this baseplate; therefore, all initial conditions for velocity and force can be set to zero. The strong forms of the equations that govern all of these conditions are shown in Equations 2, 3 and 4.

$$-\boldsymbol{\nabla} \cdot \boldsymbol{\sigma} = \boldsymbol{F}\mathbf{v}, \quad \boldsymbol{\sigma} = \mathbf{s}$$

Equation 2

$$\boldsymbol{s} - \boldsymbol{s}_0 = (\boldsymbol{\epsilon} - \boldsymbol{\alpha}\left(\boldsymbol{T} - \boldsymbol{T}_{ref}\right) - \boldsymbol{\epsilon}_0)$$

Equation 3

$$\boldsymbol{\epsilon} = \frac{1}{2}[(\boldsymbol{\nabla u})^{T} + \boldsymbol{\nabla u}]$$

Equation 4

Equation 2 is the main solid mechanics equation, where the gradient of stress is proportional to the force in the *v* direction. Equation 3 shows that the stress in Equation 2 is related to the strain and the temperature of the material, which was set at room temperature for this system. Equation 4 shows that the strain shown in Equation 3 is related to the direction gradient in the *u* direction.

A mesh had to be applied so the platform could solve for the stress at each elemental node. The mesh is a triangular mesh that consists of 1131 elements and is concentrated around critical points as shown is Figure 7. Using these forces, boundary and initial conditions, Pro/ENGINEER Mechanica was able to output a finite element analysis, shown in Figure 8.

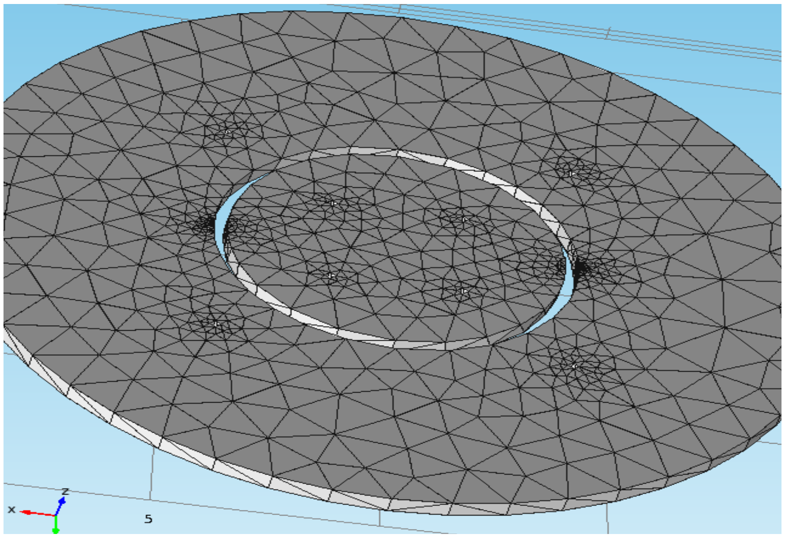


Figure 7: Baseplate Mesh

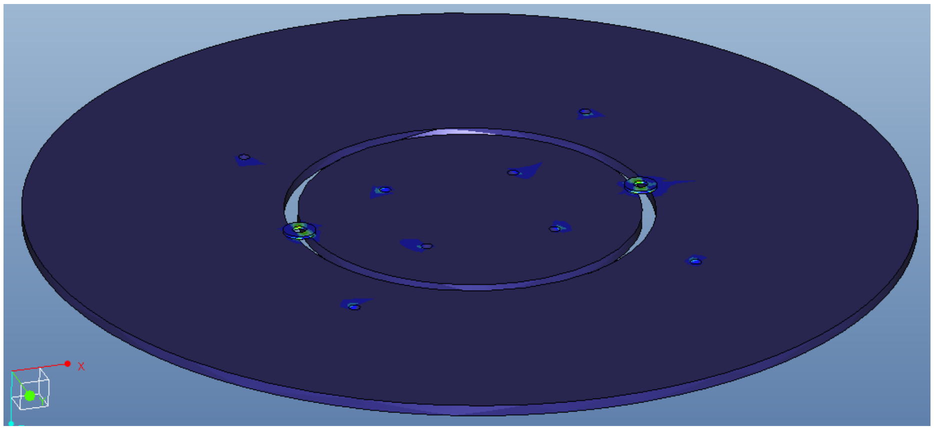


Figure 8: Mechanica FEA Output

The figure above clearly shows that most stress concentrations are located around the holes that connect this plate to the bridge and the thrust bearings that support the entire bottom half of the system. But the most instability should occur around the cutout track that the bearings ride on, so that is what this analysis is focused on. Figure 9 shows a zoomed in view of the stress concentrations around the bearings.

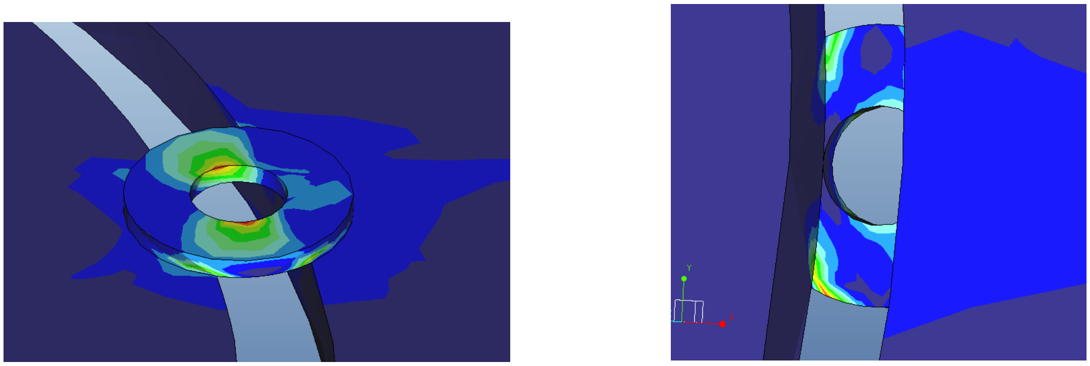


Figure 9: Thrust Bearing Stress Concentrations

The bearings show the highest stress concentrations, but these were not drawn to correct dimensions, as they were just meant to provide a surface to have a surface load applied to the baseplate, so they will be ignored. The blue and green sections on the baseplate show a stress of about 5,000 psi. The, highest stress is shown in the right side of figure 9 and is just under 5,400 psi. The material yield strength for aluminum 6061 is about 40,000 psi, so under these circumstances, the material will not fail and this gives a factor of safety of 8, which is much higher than most industry standards. The conclusion of this finite element analysis is that this system will be able to hold the load without failure and provide a sufficient factor of safety.

System Components and Analysis

Mechanism

The mechanism that will be used to control the motion of the device will incorporate a double gimbal assembly. A gimbal is a pivoted support that allows rotation of an object about a single axis. Since the mechanism will incorporate a double gimbal, this will provide the mechanism with two degrees of freedom. It will also ensure that the device can traverse the forward hemisphere. Also since it has two degrees of freedom it will require two motors to control the motion of the device.

Motors

When determining the type of motor that was chosen, the following characteristics were weighed: high torque for rapid change of direction, the feedback capabilities, accurate positioning and reasonable cost.

Originally, the three motors that were being considered were the Animatics motors, Dynamixel motors, and Baldor motors. All motors incorporate a built in motor controller, encoder, and amplifier. We concluded with our decision matrix shown below in Table 7 that both the Animatics motors and the Baldor motors were insufficient in meeting the criteria. The Animatics Smart Mortors, were too expensive at approximately $500 per motor and didn't have a high enough torque, approximately 5.4 Nm, compared to the Dynamixel Motors. The Baldor motors had a fair amount of torque at approximately 7.5 Nm but featured no integrated feedback. It is also very hard to find a supplier that sells the type of Baldor motor we were looking for with an unknown price.

The motors that were chosen are the Dynamixel motors shown in Figure 10. These motors also incorporate a built in motor controller and vary in price and torque. From the amount of torque required through calculations shown in earlier concept and prototype designs, the RX-64 and the EX-106+ will both be used. The RX-64 is approximately $280, which is much more cost effective than the previous Animatics motors. This motor has a max torque of 6.3 Nm while the EX-106+ has a max torque of 10.5 Nm. However the EX-106+ is approximately $500, which is currently outside the budget. However our client at Eglin has agreed to purchase this motor for us. This motor will be used to control the azimuth, or horizontal, movement of the system, which requires the most amount of torque. The RX-64 motor will be used to control the vertical motion of the gun since the required torque is less and the motor cost is less. These motors are also excellent in size, both being approximately 2.5 inches long. Dynamixel also has a full line of brackets, which means that fabrication of brackets is not necessary. Both motors have speeds above the required minimum of 360 deg/s. The RX-64 motor has a speed of approximately 382 deg/s while the EX-106+ has a max speed of approximately 420 deg/s. Both motors also have less than a one-degree resolution, which meets our constraint.

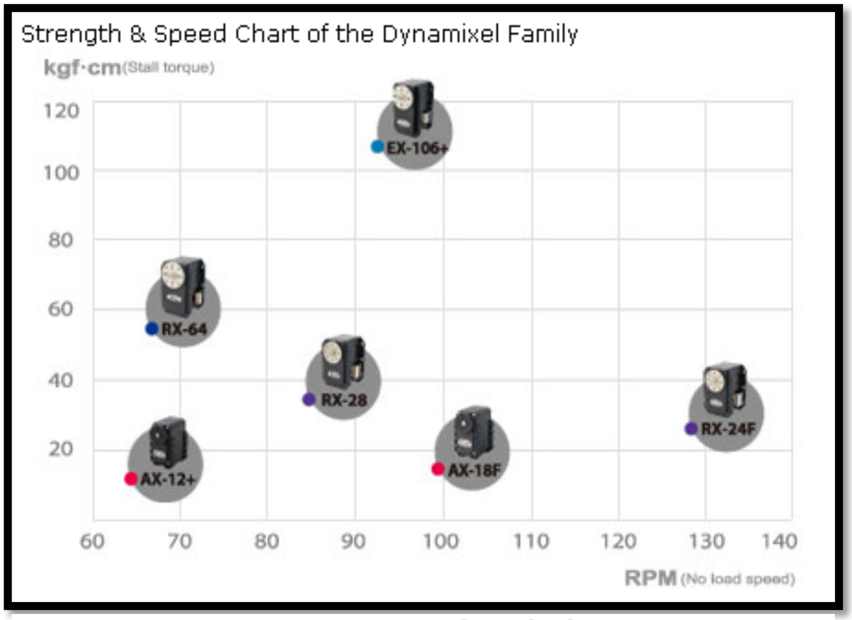


Figure 10: Dynamixel Family Chart

Motor Ranking/Decision Matrix

After researching all of the motor specifications, Table 7 compares the three motors using specific criteria explicitly laid out in Table 6. Each criterion has a ranking from 1 to 5, and using the product specifications and the values previously calculated for our system, these matrices help determine what motor is best for the prototype.

Table 6: Motor Ranking Criteria

		Criteria			
		Cost	Torque	Speed	Communication
Ranking	1	> $400	< 2.99 Nm	< 360°/s	No Feedback
	2	$300 - $399	3 Nm - 3.99 Nm	360°/s - 369.9°/s	Minimal Feedback
	3	$200 - $299	4 Nm - 4.99 Nm	370°/s - 379.9°/s	Additional Components Needed
	4	$100 - $199	5 Nm - 5.99 Nm	380°/s - 389.9°/s	Multiple Ports Needed
	5	< $100	> 6 Nm	> 390°/s	Direct Connection

Table 7 shows the decision matrix that implements the criteria outlined in Table 6. This table weights each criteria based on its importance to the final prototype. It is clear from this table that the Dynamixel Motor is the clear choice for this project.

Table 7: Motor Decision Matrix

		Concepts					
		Smart Motors		Dynamixel		Baldor	
Specifications	**Weight**	Rating	Score	Rating	Score	Rating	Score
Cost	35%	1	0.35	3	1.05	1	0.35
Torque	25%	4	1.00	5	1.25	5	1.25
Speed	25%	3	0.75	4	0.75	3	0.75
Feedback	15%	4	0.6	5	0.75	1	0.15
Total	100%		2.70		3.80		2.50

Controllers

Every servo motor today is controlled by a motor controller. Because we are only considering static testing at the moment, the system will be programmed based on an open loop. For the project, we will be using the Arbotix Robocontroller shown in Figure 12. At first, we considered using two different controllers, the Arbotix Robocontroller and the Arduino UNO, Figure 11. Each of these boards contains a microcontroller that will control the system. Although the Arduino UNO holds an ATmega328, the Arbotix Robocontroller contains an ATmega644p. Both have a clock rate of 16 MHz needed for accuracy, but the ATmega 644p contains more RAM than the ATmega328.

Figure 11 Arduino UNO motor controller

Another advantage to the Arbotix Robocontroller is that it is programmed using the same IDE the Arduino board uses. Both controllers can be programmed using the Arduino IDE, but there are premade libraries for the Arbotix Robocontroller that are made to specifically control the Dynamixel motors that we will be using for our system. Since we will be using the higher end Dynamixel motors, an Arbotix RX Bridge will be needed. This simply plugs right into the Arbotix controller, shown in Figure 12, and provides the full 1 Mbps communication. The Dynamixel motors will plug directly in to the bridge. Using the BioloidController and Motors2 libraries, controlling the motors only requires a function call. The

Arduino UNO does not have libraries available to be used with the Dynamixel motors.

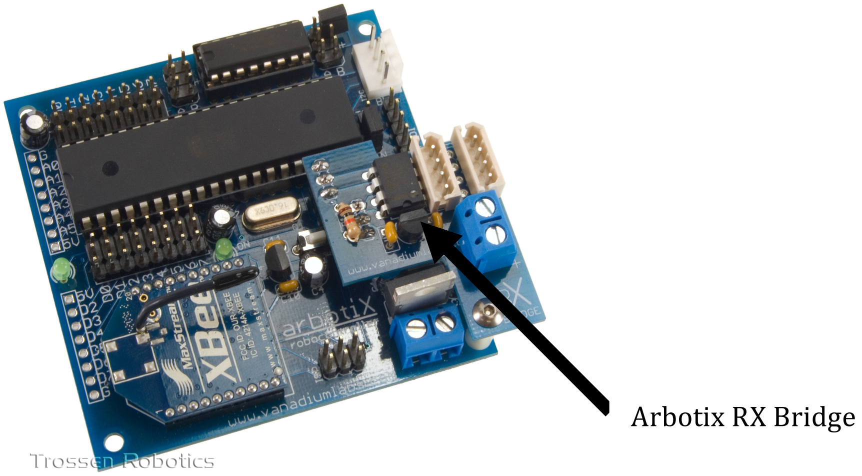


Figure 12 Arbotix Robocontroller with mounted XBee radio

We intend for the system to be wireless so that it can be remotely controlled from a different location. Because the Arbotix Robocontroller has two serial ports an XBee radio transmitting chip can be mounted on the Arbotix Robocontroller, also shown in Figure 12, giving it wireless capability. The two serial ports located on the Arbotix Robocontroller allow one port to be used by the XBEE chip and the other serial port is to be used for the Bioloid servo controller. The Arduino UNO needs a separate kit to adapt to the addition of the XBee radio, Figure 13.

Figure 13 Arduino UNO with mounted XBee radio kit

Because the Arbotix Robocontroller is more applicable to our deseign, we will use it instead of the Arduino UNO.

Control Ranking/Decision Matrix

Table 8: Controller Ranking Matrix

		Criteria					
		Clock Speed	Wireless Capability	Microcontroller	Programming Environment	"Plug and Play" Capability	Ports
Ranking	1	< 500 kHz	None	8 I/O pins	Assembly Language	Need to Order additional parts	1
	2	501 kHz - 999 kHz	1 ft - 99 ft	16 I/O pins	N/A	N/A	2
	3	1 MHz - 4.99 MHz	100 ft - 199 ft	32 I/O pins	N/A	Some Additional Programming needed	3
	4	5 MHz - 9.99 MHz	200 ft - 299 ft	64 I/O pins	Arduino IDE	N/A	4
	5	10+ MHz	300+ ft	128+ I/O pins	LabView	Ready to Use	5+

Table 9: Controller Decision Matrix

		Concepts			
		Arduino		ArbotiX Robocontroller	
Specifications	**Weight**	Rating	Score	Rating	Score
Clock Speed	12.5%	5	0.63	5	0.63
Wireliss Capability	5.0%	5	0.25	5	0.25
Microcontroller Type	12.5%	2	0.25	3	0.38
Programming Environment	25.0%	5	1.25	4	1.00
"Plug and Play" Capability	40.0%	3	1.20	5	2.00
Multiple Ports	5.0%	1	0.05	3	0.15
Total	100.0%		3.63		4.40

Power Supply

A portable power generator will be used to power the system during operation. This is a specification from the customer, because they have a generator and it keeps from having to wait for batteries to recharge. Also, the generator has a built in inverter that allows for varying voltage output, so it will be able to accommodate the power needs of the controller.

For the static tests done in Tallahassee next semester, we will not have access to the generator, since it is at Eglin. To test and analyze, rechargeable batteries will be used, since they are relatively cheep, and are lightweight and maneuverable enough to fit into the system.

Firing System

Firing System Requirements

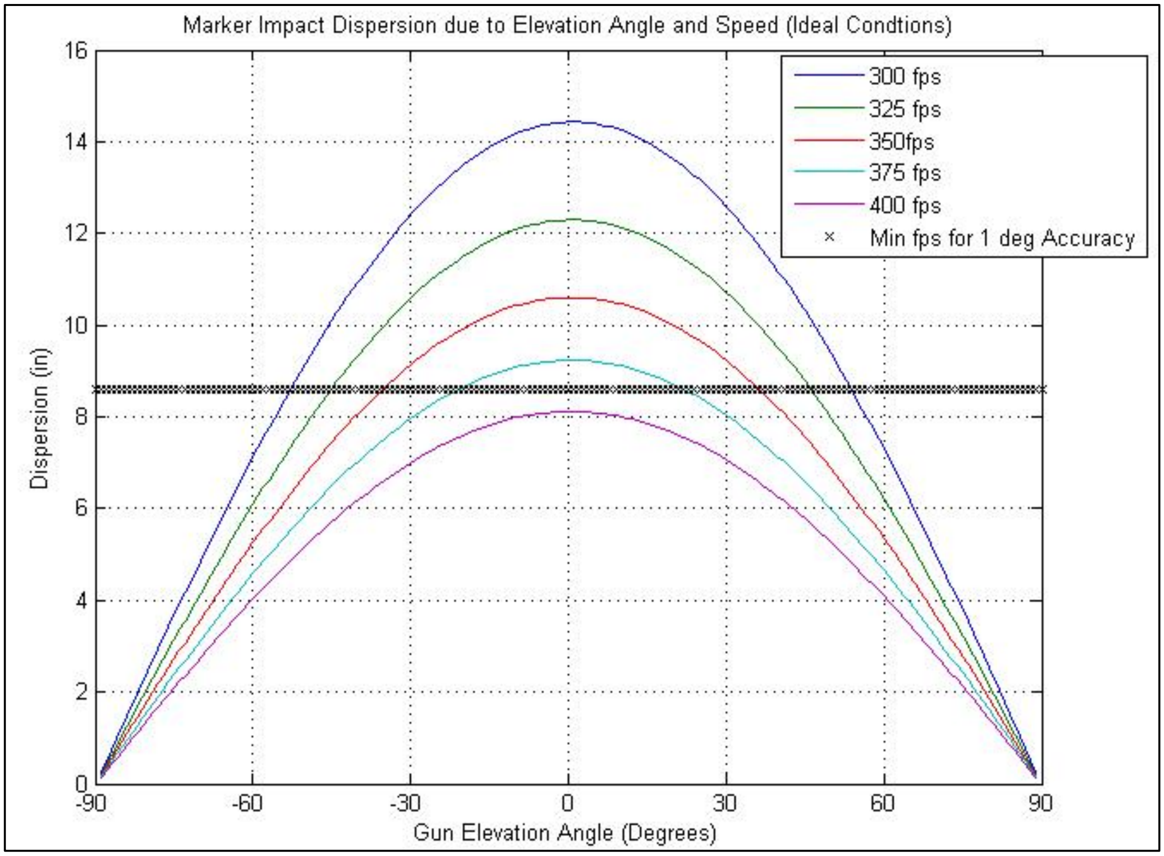


Figure 14: Shot Dispersion Due to Gravity

Before a firing system is chosen, some calculations need to be done to determine the system requirements so it will be within the required specifications. One of the customer's required specifications is that the system is accurate, which was turned into the engineering specification that it must be accurate to within a degree of its intended mark. There are multiple factors that will affect the accuracy, including wind resistance, ball aerodynamics, and even the rotation of the earth, but for simple preliminary calculations, gravity will be the only factor taken into consideration. Figure 14 shows the drop of a paintball due to gravity as the gun ranges from firing directly down, all the way to firing vertically upright. The graph shows that the maximum amount of drop that will occur when the gun is fired from a level firing position. The different colored arcs on the graph represent different muzzle velocities. Using Equation 5, we calculated the amount of drop that can occur to be 8.59 inches and still be within a tolerance of one degree at 25 meters.

$$L = \frac{\theta}{2\pi} \cdot circumference \qquad \text{Equation 5}$$

This is represented in the graph by the horizontal black line. Using all of this information, the graph shows that the muzzle velocity of the paintball needs to be between 375 fps and 400 fps to achieve accurate results. Using this information and the knowledge of the Florida State Paintball Club, it will be much easier to identify the components that meet the specifications.

Firing Mechanism

The A-5 Tippman paintball gun was the chosen firing mechanism used to fire paintballs at any given targets depending on the user's input from the computer. The Tippman is a desirable gun to use due to the fact that it is lightweight, which will not put excessive amount of weight on the motors during operation. Adjustments will be made to preserve space for other components to fit within the design, such as shortening the grip and removing the physical trigger, which will also decrease the weight of the system. Also, an electronic trigger will be integratted into the gun so firing can be executed via a remote or a set programmable firing point. A long barrel is needed to ensure accuracy and maintain consistency during the duration of testing. The barrel will be purchased from Hammerhead paintball and it is called the Freedom Fighter. This barrel is 14 inches long, which is longer than the stock barrel, and increases the accuracy at longer distances. It is also rifled, which adds spin to the balls during flight to increase the ball's aerodynamic properties.

Paintball

The balls used in paintball guns are the same used in all guns. Paintballs are basically spherical objects with a thin outer membrane and paint contained inside the membrane. There are many types of paintballs designed for different purposes, so the choice depends on the user's desired results. Evil paintballs are basic paintballs used in many paintball guns. These balls are cost effective and have different sizes to accommodate any barrel. Upon impact, the evil paintballs splatter after impact, which make measuring the center mark after impact difficult. G.O.L.F. ball paintballs are newly designed paintballs, which improve the aerodynamics for longer flight and better accuracy. These paintballs are modeled similar to real golf balls, with a dimpled surface, and these dimples are the reason for better flight aerodynamics. Another advantage to using these types of paintballs is that they have powder paint inside the membrane, therefore, after impact they will leave behind a powder point that does not run rather than a splatter. This point will allow measurement of the dispersion and accuracy to be simple and straightforward with much less guesswork when finding the center of impact. Some calibration will be needed to account for gravity and other natural occurrences.

Q-Loader Hopper

Hoppers are the basic component used in paintball guns to house and feed the paintballs into the gun's breach during firing. For this specific design, the Q-Loader Hopper will be used to house and feed paintball into the tracking system. The advantages to using a Q-Loader hopper instead of a regular hopper are the Q-Loader has flexible feeding tube, which makes it easier to implement into the system without adjusting any other components to ensure there is enough space. Unlike the basic hopper, the Q-Loader feeds the paintballs into the chamber by using a spring mechanism, which prevents jamming during operation and also prevents the paintball from prematurely bursting while in the chamber. Also, with the spring mechanism, the Q-Loader hopper can feed against gravity, which will not limit the different positions the tracking system will be placed in during operation.

Nitrogen Pressure System

The pressure system in a paintball gun is the basic component used to propel the paintball through the chamber and to its designated target. Generally most paintball guns use a gas pressure system to fire the paintballs at targets. The common gases used in the pressure system are carbon dioxide, air, and nitrogen. Testing will be done in an outdoor environment resulting in different temperature changes, depending on the time of year. Due to the outdoor environment, nitrogen will be the pressure system used for the tracking system. Nitrogen can maintain a stable pressure at different ambient temperatures, which is a desirable advantage to counter the fluctuating temperature difference. Also the customer provides nitrogen on the testing site that allows for the budget to be unaffected due to nitrogen refill.

Safety Mechanism

Safety for this system is a major concern. Because it is a live firing weapon, it is imperative that the system does not fire unless told to. The first way to make sure this does not happen is the removal of the trigger. Since the system is going to fire with an electronic trigger, there is no need to have a mechanical one, which will prevent any accidental squeeze of the trigger. The second way to make the system safe is the firing algorithm is going to be sent on a completely separate channel than the motion algorithms. This insures that there is no bad or wrong signal sent to the firing system before it is fully in place and has told the user it is ready to fire. The third measure of safety will be a keyed safety that will be wired between the controller and the triggering system. This will be a simple on/off switch that can only be switched by the designated key when the user is ready to fire. This keyed system configuration is shown in Figure 15.

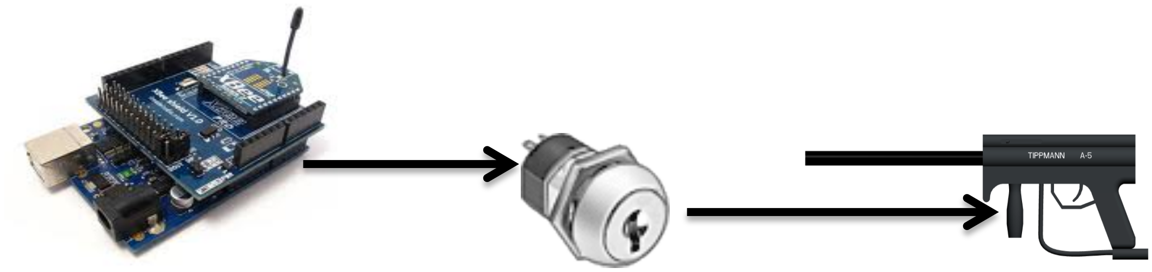


Figure 15: Keyed Safety On/Off Switch

Material and Coast Analysis

Table 10: Budget Breakdown

Paint:	
G.O.L.F Paintballs (500)	$24.95
EVIL Paintballs (2000)	$70.00
Gun & Upgrades:	
Tippmann A5 with E-Trigger	$368.45
Hammerhead Barrel	$59.00
Air Supply	$129.95
Coiled Air Hose	$30.00
Grip Rail	$20.00
Motors:	
Motors & Brackets Package	$651.40
Controller/Components:	
Controller & Bridge	$139.94
Wireless Receiver	$21.95
Wireless Remote	$24.95

Left Over	$459.41
Assembly Materials	TBD
Extra Compnents	TBD

Table 10 shows a detailed breakdown of the materials and their cost before shipping and handling. The money that is in the left over section is what is going to be allotted to raw materials such as aluminum to build the two plates and purchase any other nuts, bolts and screws that will be needed as the project progresses. This should leave enough to get everything ordered, fabricated and built within budget.

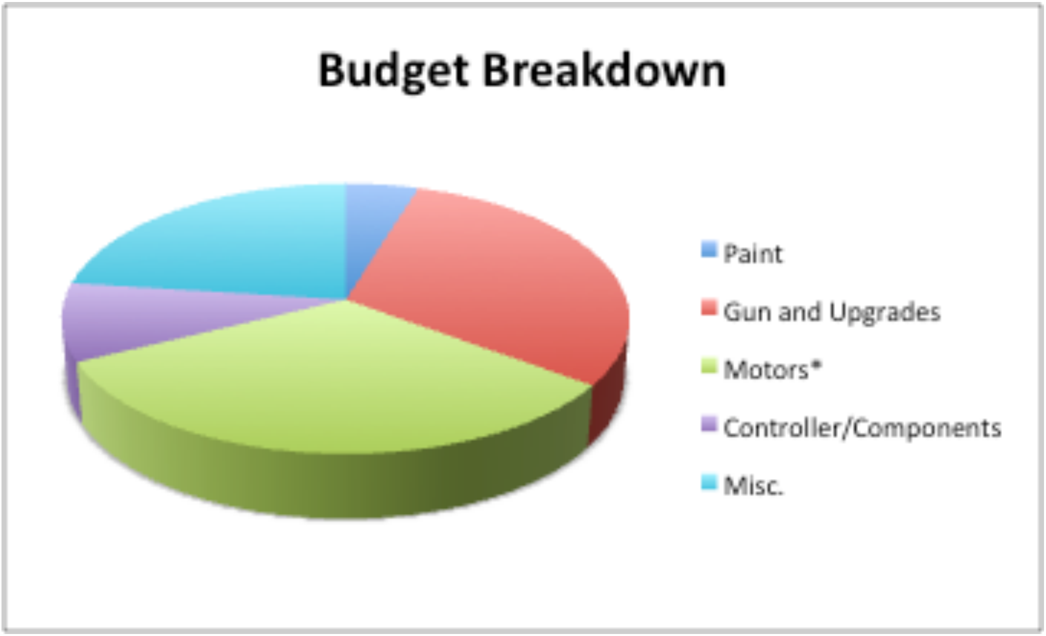
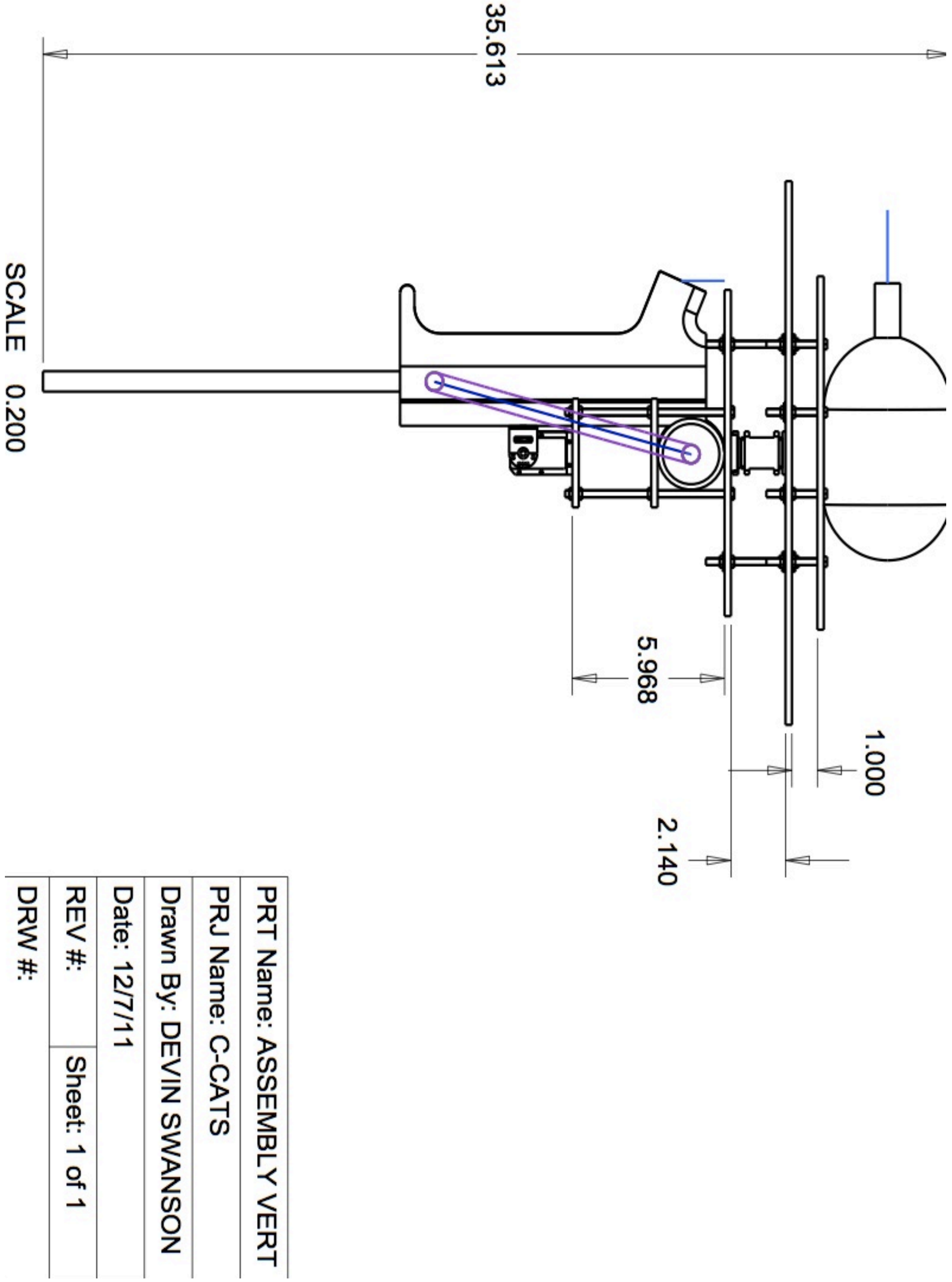


Figure 16: Pie Chart

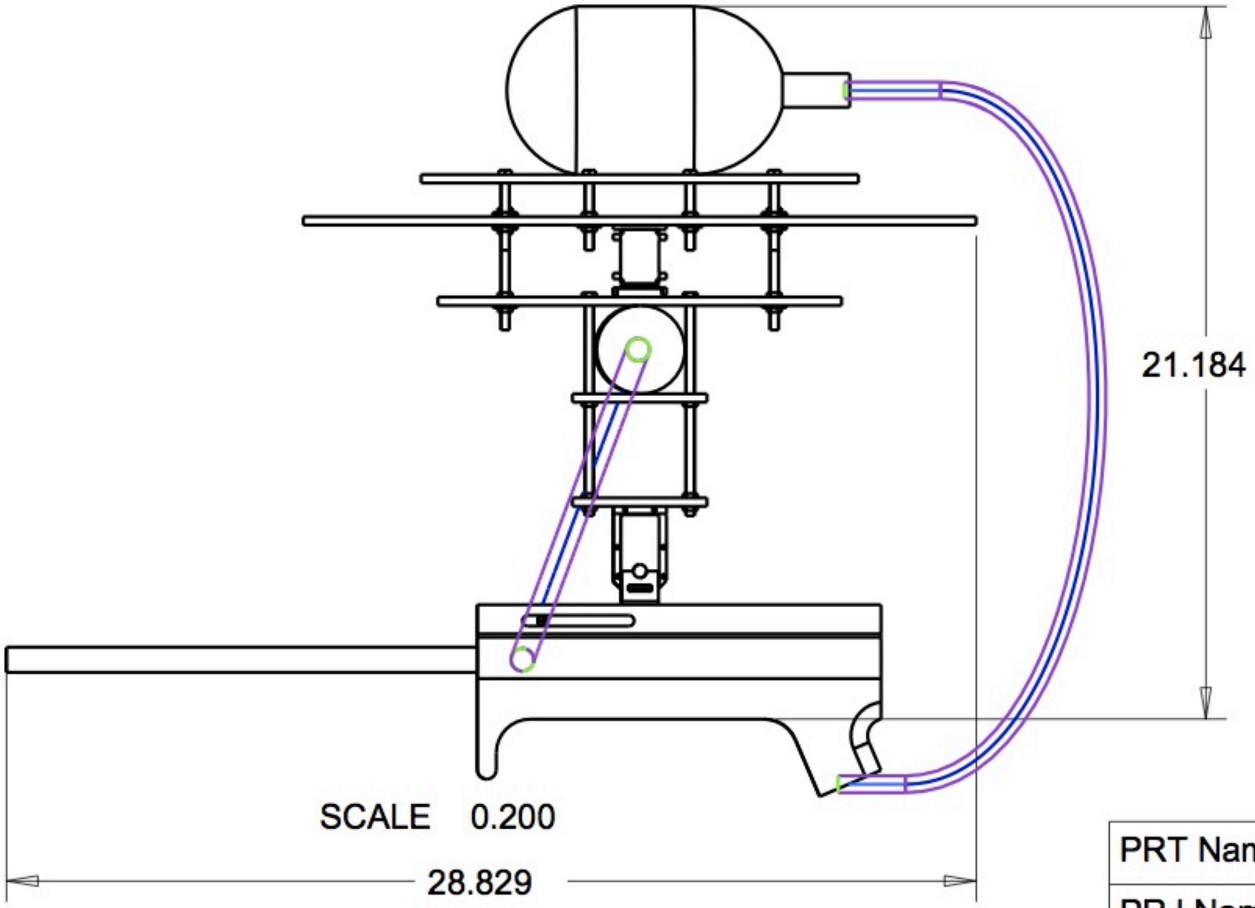
The motors section has an asterisk by it because this section only shows the cost of two smaller motors for the system. The motors in the budget are only graded to about 5 Nm, but the prototype's azimuth motor was determined to need about 9 Nm of torque. Eglin has been kind enough to offer to purchase this larger motor for us, allowing us to free up our budget for other necessary components.

Appendix

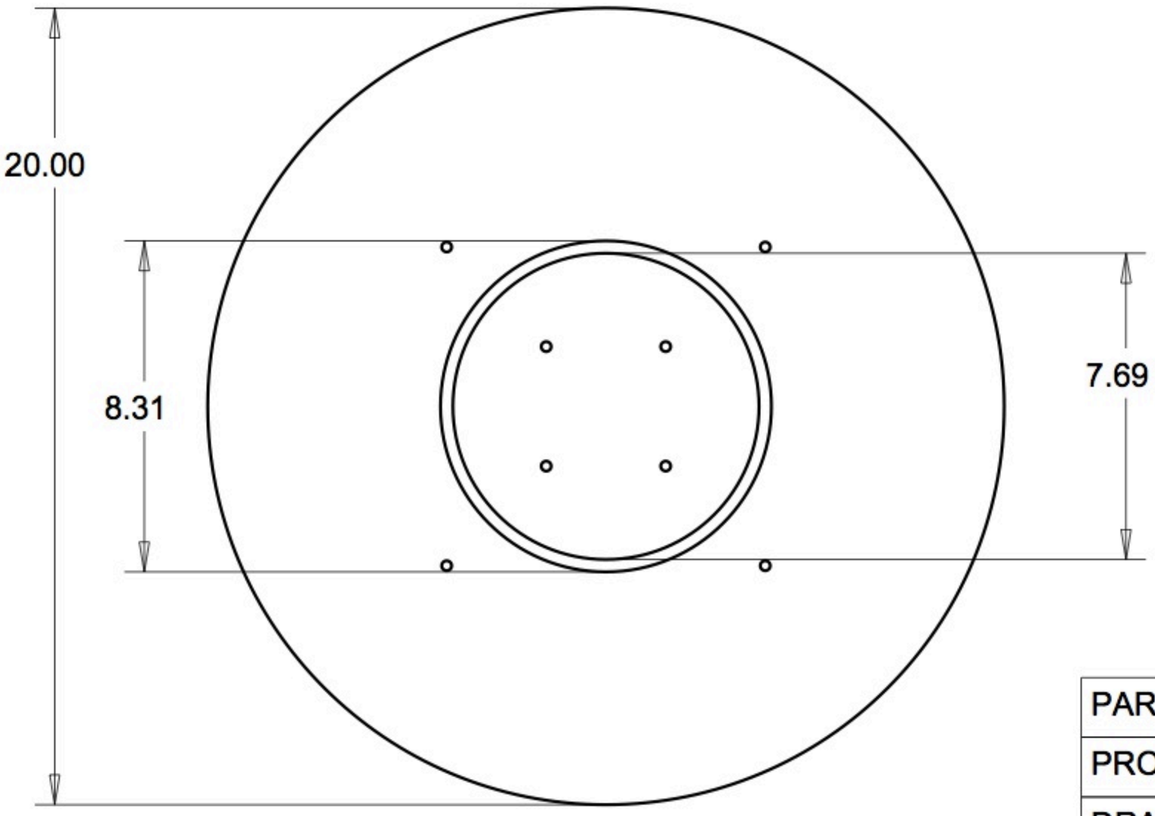
Prototype Engineering Drawings



PRT Name: ASSEMBLY VERT
PRJ Name: C-CATS
Drawn By: DEVIN SWANSON
Date: 12/7/11
REV #:
Sheet: 1 of 1
DRW #:



PRT Name: ASSEMBLY
PRJ Name: C-CATS
Drawn By: DEVIN SWANSON
Date: 12/7/11
REV #: Sheet: 1 of 1



SCALE 0.250

PART: TOP PLATE

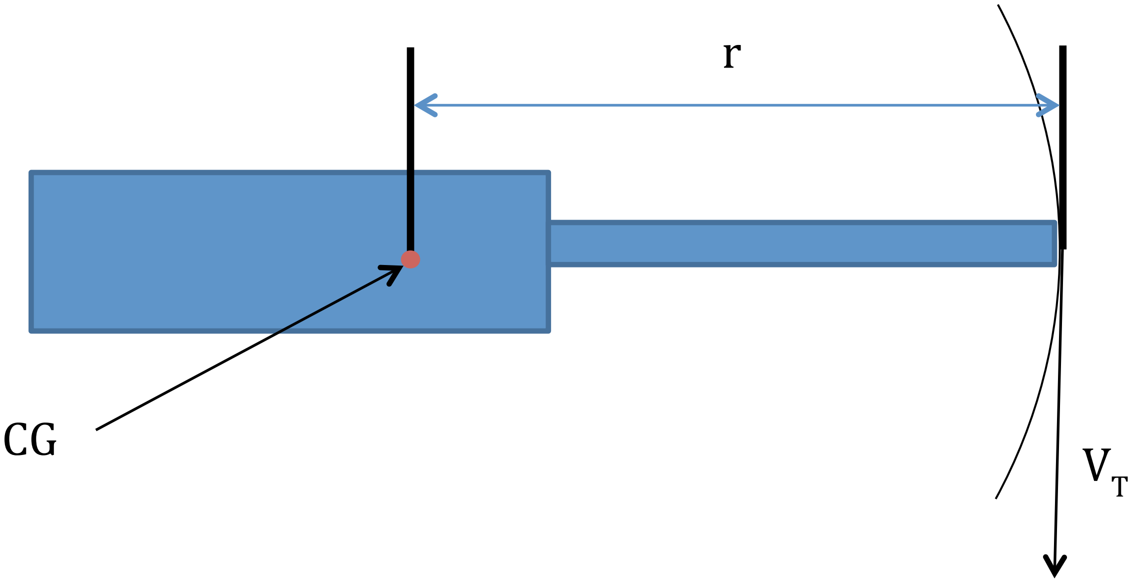
PROJET NAME: C-CATS

DRAWN BY:PARKER BRUNELLE

DATE: 12/7/11

REV: SHT:

Tangential Velocity:



$$V_{Tavg} = \omega r$$

System Acceleration:

$$\mathrm{a}_{\mathrm{Tmax}} = \frac{E_K}{m\Delta l} = \frac{\frac{1}{2}mv^2}{m\Delta l} = \frac{\frac{1}{2}v^2}{\Delta l}$$

$$\alpha_{\max} = \frac{\mathrm{a}_{\mathrm{Tmax}}}{\mathrm{r}}$$

Motor Torques:

$$\tau_{\max} = I\alpha_{\max}$$

Concept 1

Calculating Tangential Velocity

$\omega := 360 \cdot \frac{deg}{s}$ $\quad r := 19 \cdot ir$ $\quad v := \omega \cdot \imath$

$\boxed{v = 3.032 \frac{m}{s}}$

Calculating Acceleration

$a_{Tmax} := \frac{0.5 \cdot v^2}{l}$ $\quad l := 2 \cdot ir$

$a_{Tmax} = 90.498 \frac{m}{s^2}$

$\alpha_{max} := \frac{a_{Tmax}}{r}$ $\quad \boxed{\alpha_{max} = 187.522 \frac{1}{s^2}}$

Calculating Azimuth and Elevation Torque

$I_y := 90.27 \cdot lb \cdot in^2$ $\quad I_x := 101.82 \cdot lb \cdot in^2$

$\tau_y := I_y \cdot \alpha_{ma}$ $\quad \boxed{\tau_y = 4.954J}$

$\tau_x := I_x \cdot \alpha_{ma}$ $\quad \boxed{\tau_x = 5.588J}$

Concept 2

Calculating Tangential Velocity

$\omega := 360 \cdot \frac{deg}{s}$ $\quad r := 21.46 \cdot ir$ $\quad v := \omega \cdot \imath$

$\boxed{v = 3.425 \frac{m}{s}}$

Calculating Acceleration

$a_{Tmax} := \frac{0.5 \cdot v^2}{l}$ $\quad l := 2 \cdot ir$

$a_{Tmax} = 115.45 \frac{m}{s^2}$

$\alpha_{max} := \frac{a_{Tmax}}{r}$ $\quad \boxed{\alpha_{max} = 211.802 \frac{1}{s^2}}$

Calculating Azimuth Torque

$I_z := 1255.2 \cdot lb \cdot in^2$

$\tau := I \cdot \alpha$ $\quad \tau = 77.799J$

Final Prototype

Calculating Tangential Velocity

$\omega := 360\cdot\frac{deg}{s}$ $\qquad r := 18.7\cdot ir$ $\qquad v := \omega\cdot\imath$

$$\boxed{v = 2.984\frac{m}{s}}$$

Calculating Acceleration

$a_{Tmax} := \frac{0.5\cdot v^2}{l}$ $\qquad l := 2\cdot ir$

$$a_{Tmax} = 87.663\frac{m}{s^2}$$

$\alpha_{max} := \frac{a_{Tmax}}{r}$ $\qquad \boxed{\alpha_{max} = 184.562\frac{1}{s^2}}$

Calculating Azimuth Torque

$I_z := 189.01\cdot lb\cdot in^2$

$\tau_z := I_z\cdot\alpha_{ma}$ $\qquad \boxed{\tau_z = 10.208J}$

Dispersion Graph Code:

```
caliber = .686;       %paintball diameter
P = 800;              %pressure acting on paintball
m = 0.00705479239;    %mass of a paintball in kg
L = 984.251969;       %25 m converted to inches
a_g = -386.088;       %accel. due to gravity in/sec^2

v1 = 4200;
v2 = 3600;
v3 = 3900;             %initial muzzle velocities used
v4 = 4500;
v5 = 4800;

i = 0;                 %initialize for loop counter
T = -91;               %initialize for theta counter

min = 8.589218764;     %minimum allowed drop for accuracy
(in)
circ = 6184.23751;     %circumference of 25 m circle (in)

theta = zeros(1,180);
vi_x = zeros(1,180);
s_x = zeros(1,180);
t_x = zeros(1,180);
vi_y = zeros(1,180);            %initializes vectors
v_y = zeros(1,180);
s_y = zeros(1,180);
theta_arc = zeros(1,180);
arc_length = zeros(1,180);

%%%%%%%%%%%%%%%%%%%%%%

vi_x2 = zeros(1,180);
s_x2 = zeros(1,180);
t_x2 = zeros(1,180);
vi_y2 = zeros(1,180);           %initializes vectors
v_y2 = zeros(1,180);
s_y2 = zeros(1,180);
theta_arc2 = zeros(1,180);
arc_length2 = zeros(1,180);

%%%%%%%%%%%%%%%%%%%%%%%%

vi_x3 = zeros(1,180);
s_x3 = zeros(1,180);
t_x3 = zeros(1,180);
vi_y3 = zeros(1,180);           %initializes vectors
```

```
v_y3 = zeros(1,180);
s_y3 = zeros(1,180);
theta_arc3 = zeros(1,180);
arc_length3 = zeros(1,180);

%%%%%%%%%%%%%%%%%%%%%

vi_x4 = zeros(1,180);
s_x4 = zeros(1,180);
t_x4 = zeros(1,180);
vi_y4 = zeros(1,180);           %initializes vectors
v_y4 = zeros(1,180);
s_y4 = zeros(1,180);
theta_arc4 = zeros(1,180);
arc_length4 = zeros(1,180);

%%%%%%%%%%%%%%%%%%%%%%

vi_x5 = zeros(1,180);
s_x5 = zeros(1,180);
t_x5 = zeros(1,180);
vi_y5 = zeros(1,180);           %initializes vectors
v_y5 = zeros(1,180);
s_y5 = zeros(1,180);
theta_arc5 = zeros(1,180);
arc_length5 = zeros(1,180);

for t = -90:1:90
    %%%%%%%%%%%%%%%%%%%%%%%% 300 fps:

    i = i+1;                    %counter
    theta(i) = T + i;           %counts down theta


    vi_x(i) = v1*cosd(t);      %initial velo in x direction
    s_x(i) = L*cosd(t);        %displacement in x direction
    t_x(i) = s_x(i)/vi_x(i);   %time to reach impact


    vi_y(i) = v1*sind(t);     %initial velo. in y direction
    v_y(i) = vi_y(i) + a_g*t_x(i);%final velo in y direc
    s_y(i) = .5*(v_y(i) + vi_y(i))*t_x(i);  %displace in y


    theta_arc(i) = abs((abs(t) -
atand(abs(s_y(i))/s_x(i))));
             %angle the impact made with intended target
```

```
    arc_length(i) = (theta_arc(i)*(pi/180)*circ)/(2*pi);
             %total distance the ball dropped during flight


    %%%%%%%%%%%%%%%%%%%%%%%%%%%%% 325 fps:

    vi_x2(i) = v2*cosd(t);
    s_x2(i) = L*cosd(t);
    t_x2(i) = s_x2(i)/vi_x2(i);

    vi_y2(i) = v2*sind(t);
    v_y2(i) = vi_y2(i) + a_g*t_x2(i);
    s_y2(i) = .5*(v_y2(i) + vi_y2(i))*t_x2(i);

    theta_arc2(i) = abs((abs(t) -
atand(abs(s_y2(i))/s_x2(i))));
    arc_length2(i) = (theta_arc2(i)*(pi/180)*circ)/(2*pi);

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%% 350 fps:

    vi_x3(i) = v3*cosd(t);
    s_x3(i) = L*cosd(t);
    t_x3(i) = s_x3(i)/vi_x3(i);

    vi_y3(i) = v3*sind(t);
    v_y3(i) = vi_y3(i) + a_g*t_x3(i);
    s_y3(i) = .5*(v_y3(i) + vi_y3(i))*t_x3(i);

    theta_arc3(i) = abs((abs(t) -
atand(abs(s_y3(i))/s_x3(i))));
    arc_length3(i) = (theta_arc3(i)*(pi/180)*circ)/(2*pi);

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%% 375 fps:

    vi_x4(i) = v4*cosd(t);
    s_x4(i) = L*cosd(t);
    t_x4(i) = s_x4(i)/vi_x4(i);

    vi_y4(i) = v4*sind(t);
    v_y4(i) = vi_y4(i) + a_g*t_x4(i);
    s_y4(i) = .5*(v_y4(i) + vi_y4(i))*t_x4(i);

    theta_arc4(i) = abs((abs(t) -
atand(abs(s_y4(i))/s_x4(i))));
    arc_length4(i) = (theta_arc4(i)*(pi/180)*circ)/(2*pi);

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% 400 fps:
```

```
    vi_x5(i) = v5*cosd(t);
    s_x5(i) = L*cosd(t);
    t_x5(i) = s_x5(i)/vi_x5(i);

    vi_y5(i) = v5*sind(t);
    v_y5(i) = vi_y5(i) + a_g*t_x5(i);
    s_y5(i) = .5*(v_y5(i) + vi_y5(i))*t_x5(i);

    theta_arc5(i) = abs((abs(t) -
atand(abs(s_y5(i))/s_x5(i))));
    arc_length5(i) = (theta_arc5(i)*(pi/180)*circ)/(2*pi);

end


plot(theta,arc_length2,theta,arc_length3,theta,arc_length,t
heta,arc_length4,theta,arc_length5,theta,min, 'blackx'),
grid on, xlabel('Gun Elevation Angle
(Degrees)'),ylabel('Dispersion (in)'),
title('Marker Impact Dispersion due to Elevation Angle and
Speed (Ideal Condtions)'),
legend('300 fps','325 fps','350fps','375 fps','400
fps','Min fps for 1 deg Accuracy')

%above is the graph arc length vs. shooting angle
```