Fetching Interactive Dog Occupier (FIDO)

A Major Qualifying Project
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Submitted by

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Abstract

Finding time and energy for playing with dogs can be difficult. Elderly or physically disabled dog owners may lack the strength or endurance to train and exercise their pets. Our FIDO project designed a tennis ball throwing center to entertain a dog. It focuses on the overall design and performance of a new product. Mechanical systems for elevation, rotation and launching of a tennis ball were analyzed and studied for fast operations. The footprint of the FIDO design was configured to allow a single person to move, relocate, and set it up. The time required for a subsequent ball toss was designed to be less than 15 seconds. The team designed and fabricated an aesthetically appealing outer housing of FIDO including painted frame, laser cut-to-fit acrylic side panels, and finished wood as the top and bottom bases for the product. The system provides interactive input for both interior and exterior operation.

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Executive Summary

Playing fetch is one of the oldest activities that a dog and its master can partake in. Fetch is a simple activity where a master will throw an object, generally a ball, for the dog to retrieve. Once the dog retrieves the object to its master, a positive reinforcement action of some kind is done by the master. The positive reinforcement can be as anything from delivering a verbal phrase such as "Good Job!" or giving the dog a treat. Once this action has been done, the dog is willing to fetch the ball over and over again. This activity of playing fetch is FIDO's primary purpose.

Today, some dog owners have difficulty finding time to perform this crucial activity, so a variety of products exist on the market today to address this need. These devices allow dogs to play fetch on their own. These devices are only able to partake in half of the activity, the fetching part. Currently, there is no device on the market which is able to fulfill both parts of the fetch activity: the fetching part and the positive reinforcement part.

The first iteration of FIDO aimed to address this need. Its focus was to address the fetching activity as a whole by creating a device that could play fetch and deliver positive reinforcement to the dog in question. While the first iteration, or prototype, managed to achieve this, the speed and maneuverability of the device was a major design concern. This is where the second iteration focus was centered.

FIDO 2.0's focus was more geared towards improving all aspects of the fetching part of the activity, mainly shortening the time between ball delivery to ball firing, as well as adding versatility so it can be used indoors or outdoors. FIDO 2.0's launching system design allows for a variety of firing ranges which not only stimulates that dog's interest, but allows for the possibility of indoor use. With a rotating nozzle head, FIDO 2.0 can also alter its firing, or elevation, angle as well as its firing direction. The ball is able to be fired at any inclination angle between 0° and 45°. In addition to the angle ranges, the new firing system in conjunction with a ball regulator system allows for an increased ball firing rate. The ball regulator allows for the device to be loaded with multiple balls without the device firing all of them at once. As with the previous iteration, safety to the dog and its owner is of the utmost concern. To address this, the device has been outfitted with sensors which can detect people and dogs that are in the line of fire, that when tripped prevent the device from firing. The final constructed prototype can be seen in Figure 1.

Figure 1 - FIDO Complete Working Prototype

Speed, size, and efficiency were the three main elements that needed to be addressed in the second iteration. While the positive reinforcement elements of the device can be refined further from the first iteration, it became apparent that a completely new design would need to be created for the fetching side of FIDO.

The first design improvement made was the firing system. FIDO 2.0 uses two DC motors to rotate wheels which launch the ball, similar to most pitching machines that are on the market today. This design proved to be the best due to its simplicity, reliability, and manufacturability. This design also allowed for an increased firing rate as the time needed for the wheels to spin up was around five seconds. Though this design proved to be the best, alterations to the wheels were needed to compensate for ball compression.

The rotating nozzle design was determined in order to limit the number of systems on FIDO 2.0. The rotating nozzle allows for control over the fire angle and direction. This essentially collapses the two systems needed to achieve this same effect into one. This also allows for a user's input to fine tune the setting for the fetching session, giving the device more flexibility.

The ball regulator was created as a 3D part, in order to get a custom light part. Although this technique would be expensive when used in manufacturing, it is cost effective for prototyping purposes. The regulator consists of two parts: a cylindrical tube, and a u-shape regulator. As the balls enter, they are stopped by the u-shape regulator. An infrared sensor is then tripped when a ball is ready to be fired. The u-shape regulator is then rocked by a servo motor to load one ball into the launcher while keeping the others from entering.

All these elements are then controlled via a Raspberry Pi controller. A Raspberry Pi was used over an Arduino Uno due to its greater computing power and its ability to create user interfaces when needed. This could have been created on the Arduino Uno, but it would have trouble keeping up and cause lag in the overall system.

FIDO 2.0's octagonal frame is composed of acrylic, rolled weldable steel, and birch wood due to the inability to 3D print the entire frame in a circular shape. The design chosen was an octagon for easy assembly and building. The metal frame provides a strong and sturdy infrastructure for the device, while the acrylic allows the owners to have visibility into the inner components.

This second iteration of FIDO was a good demonstration of a new refined fetching system. Although this was a great step in the right direction, testing the prototype showed that a few minor adjustments in the firing system needed to occur. Once those adjustments occurred, mainly the wheel size, the final proof of concept on a new firing mechanism was complete.

Upon completion of the prototype, some further refinements should occur in future iterations. The areas that would require more testing and design would be new positive reinforcement systems, which could be added to the current system. Also, minor elements in the launcher should be looked into greater optimization. These elements, mainly methods on delivering positive reinforcement, should be the focus of the next iteration.

Chapter 1: Introduction

Playing fetch is one of the oldest activities that a dog and its master can partake in. Once the dog retrieves the object to its master, a positive reinforcement action of some kind is done by the master. The positive reinforcement can be as anything from delivering a verbal phrase such as “Good Job!” or giving the dog a treat. Once this action has been done, the dog is willing to fetch the ball over and over again. Today, some dog owners have difficulty finding time to perform this crucial activity, so a variety of products exist on the market today to address this need. However, these devices are only able to partake in half of the activity, the fetching part. Currently, there is no device on the market which is able to fulfill both parts of the fetch activity: the fetching part and the positive reinforcement part.

The purpose and goals for the Fetching Interactive Dog Occupier (FIDO 2.0) are to provide an entertainment center for a pet with a launch frequency several times a minute and distance repeatability. Reductions in overall size and weight of the device are also desired for easier carrying and storage of the product. The goal was to create a design that would increase the range of elevation by 15° (0° - 45°) and decrease the time taken for the design to reach the maximum angle from the minimum angle.

A Raspberry Pi system was used to control the center for both interior and exterior operations. For outdoor conditions the launching elevation would increase and the motors would be running at a higher duty cycle for greater distance launches. Indoor conditions require short launches limited elevations to prevent damaging windows and other valuable objects in the owner’s home.

Chapter 2: Background Research

IDO is one of many toys out on the market known as Automatic Dog Ball Throwers. These types of automatic dog toys use a mechanical system similar to a ball pitching machine, in order to play fetch with the dog. There is a dispenser hopper where the balls are held and a couple of DC motors used to spin two wheels to launch the ball.

Pitching machines are quite simple in design and are used in a variety of sports; most common of which are tennis and baseball. While the design of the pitching machine changes depending on the sport, they all follow a fundamental base design. The most common pitching, known as a circular pitching machine, utilizes two to three spinning wheels mounted either vertically or horizontally. The ball is fed through the wheels and then fires off in the direction aimed. Since each wheel has its own motor, this allows the machine to throw different pitches by imparting different spins on the ball.

The wheels used to fire the balls are also designed to be very heavy. This allows for the pitching machine more power efficient. By have large heavy wheels, the kinetic energy stored in them is quite high. This leave of energy is comparatively quite large compared to the loss of energy that occurs when the ball passes through them. This means that the rotational velocity of the wheels hardly decreases meaning that the motors don’t need much energy to keep the wheels at speed, due to the inertia of the wheels.

Figure 2 - GoDogGo Remote Fetch Machine

This spinning wheel design is what most automatic dog pitching machines on the market use. The most popular two are the iFetch (Figure 3) and the GoDogGo (Figure 2). The GoDogGo is an automatic outdoor pitching machine that is to hold multiple balls at a time. It has a large hopper which is able to hold all multiple balls on top of the device [7]. The balls are then able to flow down into the firing section of the device. The device then spins a wheel with a protruding triangular part. This acts like a foot and kicks the ball out. This style of firing is not commonly used since it makes it difficult to spin the wheel at the right speed in order to achieve a certain distance.

Figure 3 - iFetch

The iFetch is different in comparison to the GoDogGo device. While the GoDogGo device uses a unique firing system, the iFetch follows the more common method of using spinning disks to fire a ball. The iFetch was a kickstarter device which became one of the more famous dog toy fetching machines. It is a small device, mainly intended for indoor use, which can pitch balls at distances of 10, 20 and 30 feet [9]. It comprises of a large funnel which the balls are inserted into. The iFetch can only pitch balls with diameters of 1.5 inches, which is smaller than the average sized tennis ball at 2.5 inches [9]. Once a ball is put in the funnel, it gets stopped before it enters the firing chamber. This acts as a delay as well as a unique safety feature. When the ball is stopped by the device, the opening to the wheel is blocked by the ball. This blocks up access to the firing area as the wheels spin up. . Once the wheels are at speed, the ball is then allowed to drop into the firing chamber and it gets pitched. The way the iFetch reaches different distances is not be altering the firing angle, but rather through altering the rotational velocity of the wheels used to fire the ball.

Using the same theory of design as a pitching and football training machines (Figure 4), one of the members searched ways to build a small scale design that would yield launching a tennis ball at a specific desired speed. The concept on how to make the ball spin was considered at the beginning of the project however a considerations on the space the parts would occupied and the additional weight they would provide to the device rule out the considerations. For the FIDO device timing for loading and shooting the ball was a key factor which needed it improvement. Finding an appropriate small motor with the ability to obtain high speed in a small time frame and one that would not require frequent maintenance was desirable. Diving into the designs of small drones, a motor known as a three phase brushless DC motor was found.

Figure 4 - Pitching Machine

BLDC motors primary parts are the rotor, stator, stator windings, and the rotor magnets. Currently two types of BLDC motors are found in the market, the Inner rotor design and the outer rotor design. For the outer rotor design the windings are located in the core of the motor. The rotor magnets in the design surround the stator windings. By using this particular design the windings behave as an insulator which reduces the heat rate of dissipation from the motor. Due to its design, the outer motor operates at lower cycles or at lower rated current. The stator windings surround the motor and fixed to the housing of the Inner rotor design. The main advantage from this design is the ability to dissipate heat. This is convenient because the heat dissipation directly impacts the rotor ability to produce torque. The motors also are built with and without sensors to determine the location before operating. For the purpose of the project the sensor-less motor was chosen since location of the wheels is insignificant for the launching. BLDC are set up with a control motor which controls the amount of power deliver to the motor to operate. The function of the controller is to control the average current flow through the coil. The Controller achieved controlling the average current by switching the supply voltage to the coils on and off. By controlling the current flow a desired speed or torque of the motor can be varied.

The overall BLDC motors advantages are their capability to operate at high speeds (such as 10,000 rpm), the responsiveness and quick acceleration, high power density, high reliability. The important factor observe in the motors was that they do not contain brushes, which reduce frequent maintenance which extend their life expectancies of over 10,000 hours. BLDC are set up with a control motor which controls the amount of power deliver to the motor to operate.

Ultimately, a pitching machine became the base idea for the firing mechanism. Unlike other fetching devices with light plastic wheels, FIDO 2.0 would take a more traditional firing system with heavier wheels. Weight, size, and cost will be the main factors that must be considered during the design process. Based on the search a small accessible device is ideal since the existing models are currently compact and easy for transporting purposes.

Chapter 3: Design Process

In the beginning of A-Term, the design of FIDO was split into three major components: Elevation, Launching, and Rotation. Each member dedicated time to provide ideas on how to improve upon the working model. For each component, each member searched the internet to provide three potential designs that would satisfy the component requirements. In the following sections, the top mechanisms considered for each component are shown.

A design matrix was made within each component to choose the best option. Due to the organized structure the matrix provides, each mechanism is listed horizontally and evaluated by key factors of interest. Factors such as safety, cost, range of motion, ease of repair, and speed were taken into consideration in the structure matrix and weighted to the team's discretion. Once each mechanism was evaluated with numerical values, the numbers were added to check which mechanism was the most beneficial to the project.

In B-Term, a design to combine both the elevation and rotation components of FIDO into one single aiming component was considered. The new design reduces the number of parts, reduce the number of motors, and reduce the weight and height of the overall structure.

The design and components of FIDO undertook some changes throughout C-Term. Due to spacing issues, the group decided to increase the base to be 22 in. by 22 in. from the previous model of 20 in. by 20 in. The base material used was ⅜ in. plywood obtained from Atlas Box & Crating Co Inc. A decision to make one whole unit rather than having a two stage unit in which the smaller structure built would be supporting a similar but taller structure. The newly welded base would have been placed on top of a plywood board.

During C-Term one of the main focuses was reducing the total height of the structure which currently was set to 24 in. By looking into methods to reduce the height, relocation of the pinwheel loading device were considered. After bouncing some ideas back and forth with the professor, the idea of a 3D printed loader was pursued. By choosing the idea on the loader, the team re-measured the current existing FIDO structure to obtain a new estimated height.

3.1 Preliminary Designs

This section will outline the different preliminary designs and iterations of the different components of FIDO (launching, rotation, elevation, and loading) undertook. The process of deciding which design iteration to pursue and the reasoning behind the decision is explored in this section.

3.2 Elevation Systems

A website containing numerous mechanical mechanism movements [5] was used in the search for potential mechanisms for the elevation component of FIDO. Three designs were chosen: a pulley system, a quick return crank, and an air pump motion. The chosen mechanisms are shown below in Figure 5.

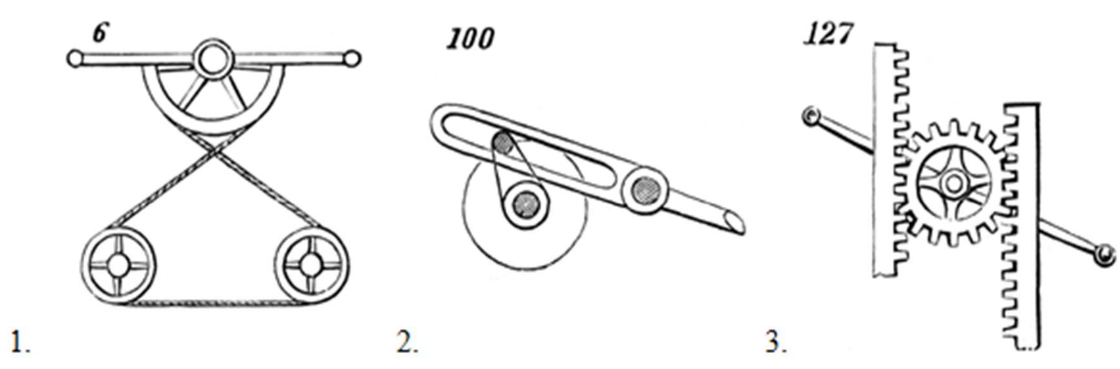


Figure 5 - Top Three Designs for Elevation

Attribute (Weight)	Design 1	Design 2	Design 3
Safety (5)	3	4	3
Cost (3)	4	3	3
Range of Motion (4)	5	3	4
Footprint (4)	3	4	2
Ease of Repair (3)	4	3	2
Speed (4)	4	2	3
Total	87	74	66

Table 1 - Design Matrix for Elevation

According to the design matrix (**Table 1**), Design 1 (pulley system) is the best vertical motion system for FIDO. A design mimicking the pulley system was implemented, which included using a servo motor and placing it on one of the two small wheels. Using the servo motors would allow the device to achieve both forward and backwards motion. Modifications to the pulley system design were made in which the wheels were ruled out and replaced by two new options. The first option was placing a wire by the far right side of the elevation base and the other end of the wire would be attached to a servo motor. The motor would be used to bring the base back to 0° after being elevated by to 45° by a counter weight that would be place in the far left hand. The second option was using a shaft that would connect to the middle of the elevation base and using a servo motor to control the elevation. Since the launcher system (which weighs approximately 6.4 lbs.) would be the heaviest part on the base, the spinning wheel's weight would be insignificant.

Initially, the elevation base had a length of 12 in. by a width of 8 ½ in. Due to implications of exact locations of the launching system parts and the pinwheel, the elevation base, as well as the height of the supporting stand for the base, was reconsidered. The new base that was built in SolidWorks contained a length of 16 in. by a width of 12 in. The thickness of ¼ in. from the previous consideration was used with the new design. The base would rotate about its center which causes a vertical displacement length of roughly 5.7 in. from 0° to 45°. The height of the supporting stand was 8 in. to allow a clearance of 2.3 in. as the base rotates for launching. A servo motor was chosen for the elevation because the range of motion for the platform is 45° rotated up or down. A servo motor is designed to achieve this motion. Figure 6 below shows the elevation system configuration.

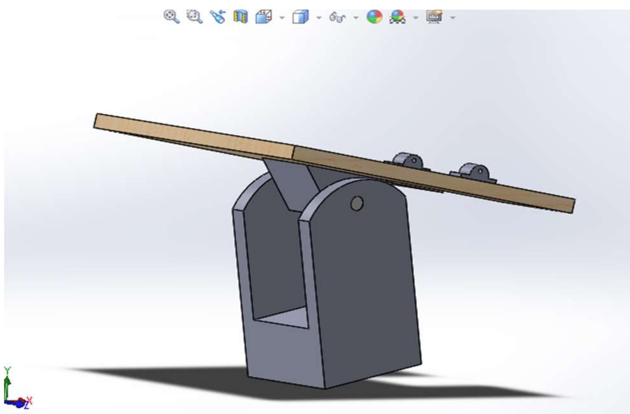
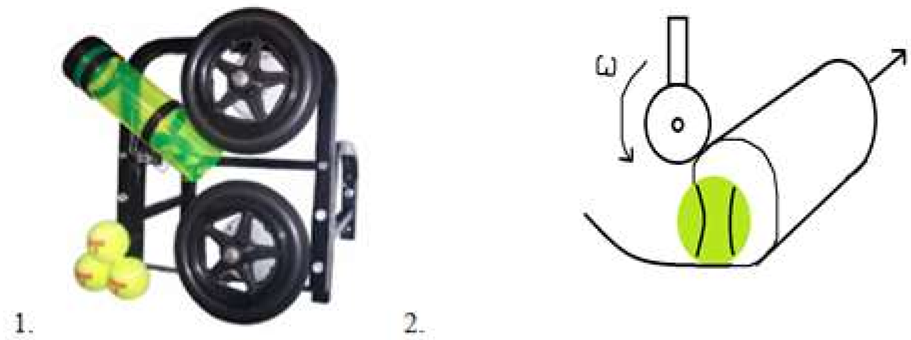


Figure 6 - Initial Elevation Configuration

3.3 Launching Systems

A variety of possible designs for the launching system were consulted, but eventually settled upon two potential designs: Dual Rotating Discs (Tennis Ball Launcher), and Ball Spanker. The two designs are shown in Figure 7.



Note: Design 1 will be placed horizontal rather than vertical

Figure 7 - Top Two Designs for Launching

Attribute (Weight)	Design 1	Design 2
Safety (5)	3	4
Cost (3)	4	3
Footprint (4)	3	3
Ease of Repair (3)	3	3
Simplicity (3)	4	3
Launch Capabilities (5)	5	2
Total	85	69

Table 2 - Design Matrix for Launching

After consulting the design matrix (Table 2), Design 1 (Dual Rotating Discs) was the most viable option for FIDO 2.0. The design was not only the simplest but also had the greatest potential for launching the balls the fastest and furthest. In addition, the Dual Rotating Discs design has the potential for system stability and energy saving potential while in operation.

Upon selecting the Dual Rotating Discs design for the launcher, further refinement on the design began. The mechanism would consist of two 4" nylon flywheels of a thickness of 1 in. driven by two separate 3-phase brushless DC motors. With these parameters chosen, as well as a target distance of 50 ft., calculations were conducted in order to determine the required ball velocity needed as well as the desired torque needed for the motors. A firing angle of 45 degrees was chosen as it provides the optimal angle for the farthest potential distance. Next a basic projectile motion calculation combined with torque calculations were conducted to find the requirements needed for the motors (See Appendix D). A PVC pipe was used as the barrel for the launcher and would have two 2 in. slits cut into the side of the pipe allowing the flywheels to fit inside for a snug fit when launching the tennis ball. A second study was conducted to find the optimal material for balance between weight and inertia. Nylon wheels were selected for their lightweight and strength capabilities. Nylon was found to be the optimal selection for a material that would allow for a short wheel spin up time, as well as a property that would take some punishment as balls were fed through them. Initially, 3-phase DC brushless motors were selected for two main reasons: their consistency and internal ability to determine motor speed. 3-Phase motors generate an electromagnetic field, back EMF, when spinning. This back EMF creates a voltage with is sent out of the motor. A 3-Phase motor controller can then read this voltage and equate it to an rpm, which can be read by a microcontroller. Figure 8 below shows the nylon wheel-motor assembly for the launching system.

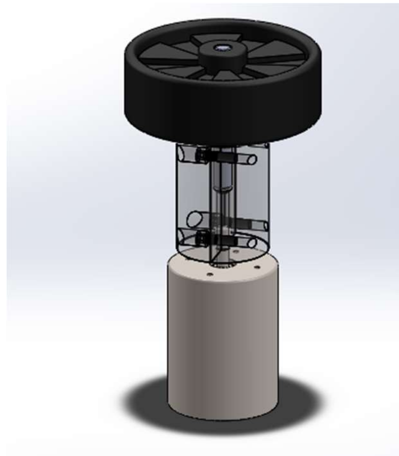


Figure 8 - Complete Motor Assembly

The wheel motor assembly was then fixed to a base plate that fixed everything together. This plate also kept the motors in the correct separation distance to allow a ball to be passed through them. The plate was affixed to an elevation plate. Figure 9 below shows the complete launching mechanism.

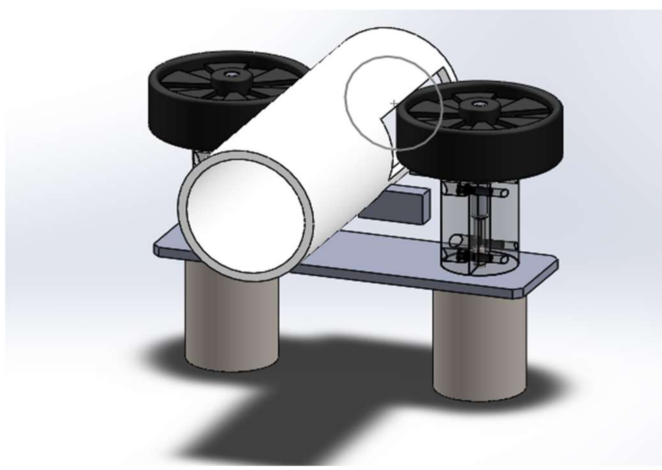


Figure 9 - Launching System Assembly

3.4 Rotating Systems

Three potential designs were considered for the rotation portion of FIDO: Lazy Susan/motor belt combo, planetary gear set, and a four-bar linkage. The three designs are shown in Figure 10.

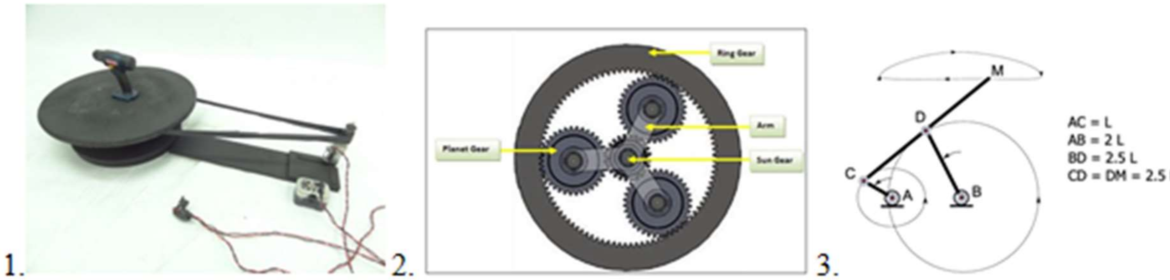


Figure 10 - Top Three Designs for Rotation

Attribute (Weight)	Design 1	Design 2	Design 3
Safety (5)	3	4	3
Cost (3)	3	3	4
Range of Motion (4)	5	5	3
Footprint (4)	2	4	1
Ease of Repair (3)	3	1	2
Speed of Rotation (4)	4	3	2
Torque (4)	3	4	3
Total	89	96	69

Table 3 - Design Matrix for Rotation

According to the design matrix (Table 3), Design 2 (Planetary Gears) is the best rotating system for FIDO. The planetary gears provide greater torque and stability, reduced volume, and greater efficiency than the other two systems.

For this application, a planetary gear set with two sun gears, one fixed to the base and the other motor driven will be pursued. Attached to the sun gears are two planet gears. The planet gears are attached to the same axle, but rotated at different speeds. The top planet gear, or planet gear #1, is attached to the ring gear, which in turn is connected to the top plate. The top plate holds FIDO together. As the motorized sun gear rotates, the ring gear (with the rest of FIDO) rotates along with it, allowing for a large range of motion for the tennis ball to be launched. A stepper motor is the optimal choice to drive the rotation application. This will allow the position of FIDO to be known precisely. Figure 11 and Figure 12 below shows the setup of the planetary gear set.

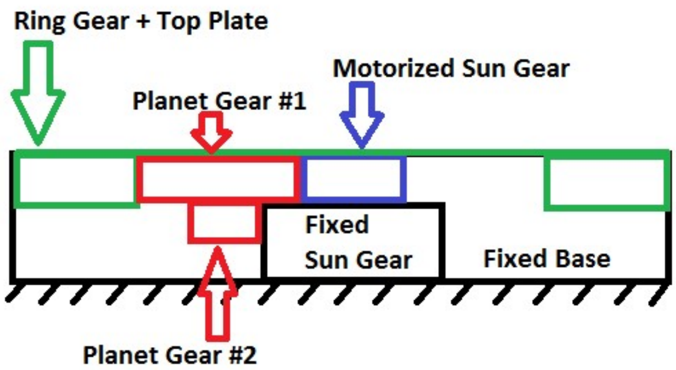


Figure 11- Planetary Gear Setup (Side View)

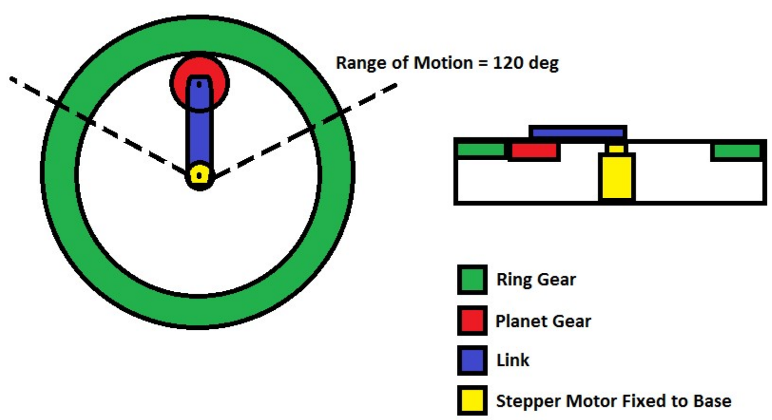


Figure 12 – Planetary Gear Set (Top View)

3.5 Loading Systems

Figuring out how to properly load one tennis ball at a time into the spinning flywheels was a challenge. To solve this problem, a pinwheel loading method was designed and implemented. When a ball is being loaded, it will first land on the flat plate of the pinwheel, triggering a sensor. The sensor determines whether the ball is or isn't on the pinwheel. Once the sensor is triggered, a servo motor powering the pinwheel will rotate the pinwheel 90°. The ball will roll off the 15° slope into the spinning fly wheels, thus launching the ball. Figure 13 shows the model of the pinwheel.

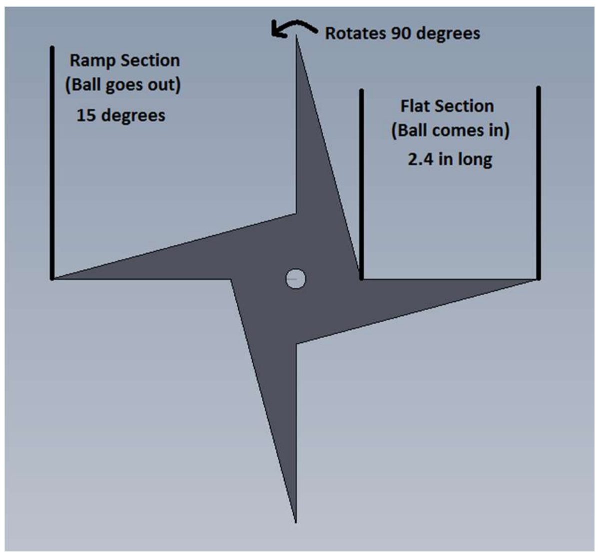


Figure 13 - SolidWorks Model of Pinwheel

Figure 14 below is the pinwheel loading assembly. The semicircular guard is used to guide the tennis ball to the spinning flywheels while the pinwheel is rotating, while also preventing the tennis ball from rolling off to the side and landing somewhere inside FIDO. The guard is attached to brackets mounted on the base (not shown in model). An axle runs through the base and the pinwheel and is driven by a servo motor, attached to the side of the base.

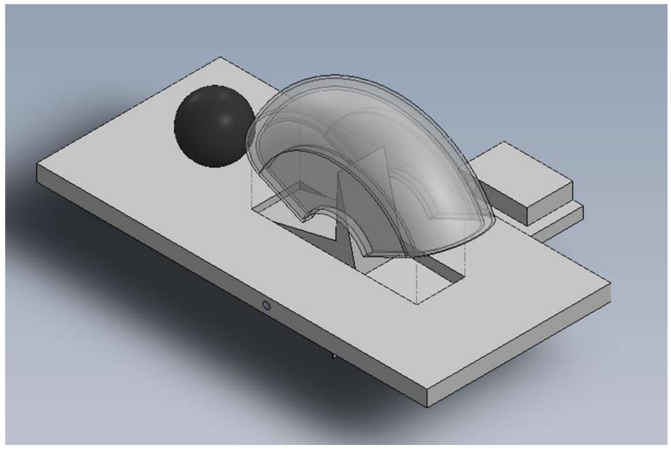


Figure 14 - Rough Pinwheel Housing Model

3.6 Motor Selection

To figure out which motors to use for each of our applications, pro and con lists of the most common types of motors were created. The Raspberry Pi has the capability to deliver 3.3 V and 5.0 V; however, some motors require higher voltages to operate. An additional power supply would have to be implemented to supply the higher voltage.

3.6.1 DC Motors

Advantage	Disadvantages
Small size	Not precise
Imply control mechanisms	Even with stable operating condition, their speed can vary
Quick starting, stopping	Performance can be degraded by dust, or bearing too much load
Wide range of speed and torque control	Require a lot regular maintenance
Cost-effective	

Table 4 - DC Motor Pro/Con Table

3.6.2 AC Motors

Advantages	Disadvantages
Lighter	Speed is harder to control
Produce less friction and heat	Devices used for communication are complicated
Long lifespan	Can be noisy
High starting torque	Require a starting switch (Induction AC motors)
Cheaper and easier maintenance	Can experience rotation slips (induction AC Motors)
No slip (for synchronous AC motors)	

Table 5 - AC Motor Pro/Con List

3.6.3 Stepper Motor

Advantages	Disadvantages
Precise positioning	Difficult to operate at extremely high speeds
Stable	Low torque capacity (often less than 2000 oz. in)
Repeatability of movement	Low efficiency (draws substantial power
Quick starting/Stopping	Noisy at high speeds
Wide speed range	Lack of feedback for the motor's position and speed (open-loop)
Long lifespan	
Compatible with digital control technologies	
Errors are non-cumulative	
More cost-effective than servos	

Table 6 - Stepper Motor Pro/Con List

3.6.4 Servo Motor

A servo motor is comprised of a motor coupled to a feedback sensor. The motor may be DC or AC, depending on the application. Servos are a high performance alternative to the stepper motor, as they operate in a closed loop rather than an open loop. Possessing a system of internal feedback, the position of a servo can be known at all times. Servo motors have the capability to operate in a multitude of different ranges, the most common ones are the ranges of 0° to 180°, 0° to 270°, and 0° to 360°. The most important note to consider while operating a servo is grounding the motor in case of an external force rotating on the servo. Manually rotating the servo causes damage to the internal gear train which is used to provide feedback to the user.

Advantages	Disadvantages
Typically small	Expensive
Large torque	Setup is complex
Do not lose torque at high rotational speed	Require an encoder and turning
Highly efficient (up to 90% efficiency with light loads	Requires safety circuits
Very accurate and precise	Frequent gearing and maintenance
Has reserve power and torque	More likely to malfunction if subjected to mechanical overload
Internal control circuit	Amount of options can be overwhelming
Less likely to have errors	
Quiet at high speeds	

Table 7 - Servo Motor Pro/Con List

3.6.5 Selections

From the pro and con lists (Table 4, Table 5, Table 6, and Table 7), elections were made for the types of motors for each different applications. The selection of motors can be seen in Table 8.

Application	Motor Type
Launching	3-Phase Brushless DC
Elevation	Servo
Rotation	Stepper
Loading	Servo

Table 8 - Motor Selection

3.7 Protected Sleeve

Keeping fingers or dog noses out of the opening from the tube as it rotates up and down 45° proved to be a challenge. To solve this problem, a protective sleeve that would fit tightly on the PVC pipe and cover up the opening as it rotates up and down was created. Figure 15 below shows the view of the sleeve and tube from the outside.

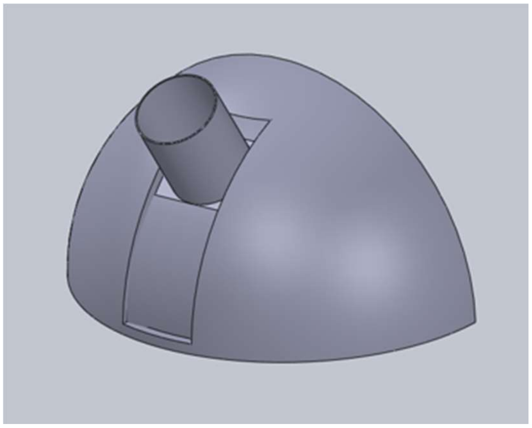


Figure 15 - Outside View of Sleeve and Tube

Figure 16 below shows the inside view of the sleeve. The length from the middle of the sleeve to the end is 4.5 in. allowing for plenty of clearance when the sleeve moves from high position (shown) to the low position (not shown). The width of the sleeve is 4 in., 1 in. greater than the diameter of the tube (3 in.). This allows the sleeve to sit flush with the semi-spherical dome structure of FIDO and allow no gaps between the sleeve and the dome. This allows the pipe to safely move up and down without fear of accidental injuries due to getting pinched in the gaps.

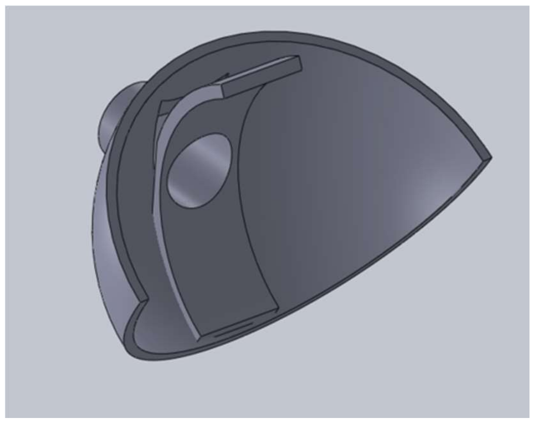


Figure 16 - Inside View of Sleeve and Tube

3.8 Aiming Systems

In order to reduce the number of parts and motors for FIDO, both the elevation and rotation systems were combined into one single system: aiming. The proposed design was to have the launcher raised to be angled 22.5° and then have a 22.5° pipe attached to the end of the launcher. The pipe would be able to rotate in a way that it could be angled so the minimum output angle was 0° and the maximum output angle was 45°, as well as being able to shoot in the left and right direction with its 360° rotation capabilities. This design increased the output range to 0°- 45°, while also satisfying the rotation requirement.

A device was designed to align two pieces of PVC pipe while one piece was placed fixed in the launcher system and the other side able to rotate freely. First, a 3D piece with the design intent to house both the rotational pipe and the fixed portion of the pipe was designed; however, the alignment of the pipe and the 3D piece would comprise the rotation ability for one of the PVC pipes. In the end, the desired motion was achieved by using a Lazy Susan bearing to fix one pipe to allow the other pipe to freely rotate.

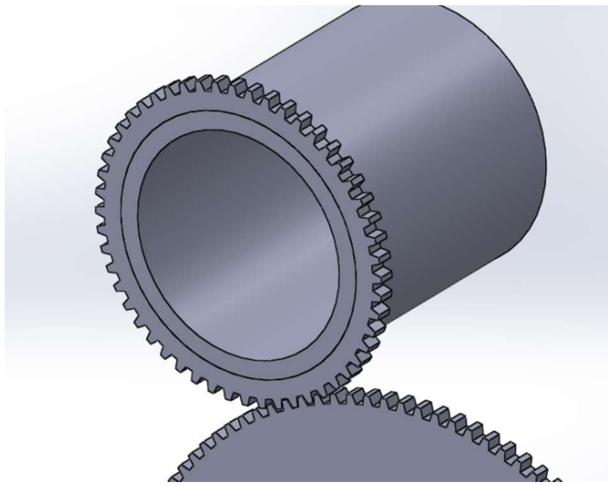


Figure 17 - Ring Gear for Pipe Rotation

One method of rotating the pipe was to laser cut an outward ring gear to be placed around the pipe and have it mesh with another gear driven by a servo motor, as shown in Figure 17 above. Fear of misalignment with the gears due to the angled operation (the launching and aiming would be angled at 22.5°) and the potential for the acrylic to break or crack hampered the design. Another method was having a toothed belt around the pipe and having a pulley rotate the toothed belt. With the same fear of misalignment, this idea was also scrapped. In the end, a regular tension belt and pulley driven device was chosen to rotate the pipe.

3.9 Preliminary Overall Designs

Figure 18 and Figure 19 below shows the first design for the overall structure for FIDO, as well as the zoning for the individual components. This design still had the elevation and rotation components as two different components and the loading component was still the pinwheel design. [illegible] e seen in

Color	Component
Blue	Pinwheel Space
Indigo	Launching Pipe Space
Purple	Dog Treat Holder
Cyan	Battery Space
Lime Green	Circuit Board Space
Orange	Elevation Space
Green	Rotation Space

Table 9 below.

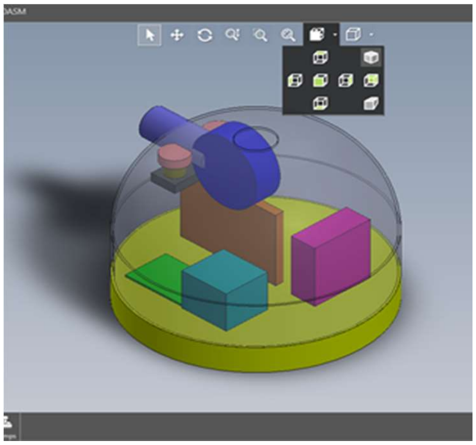


Figure 18 - Isometric View of FIDO Zoning

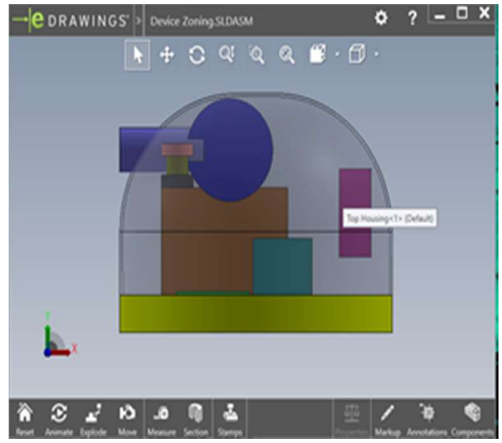


Figure 19 - Side View of FIDO Zoning

Color	Component
Blue	Pinwheel Space
Indigo	Launching Pipe Space
Purple	Dog Treat Holder
Cyan	Battery Space
Lime Green	Circuit Board Space
Orange	Elevation Space
Green	Rotation Space

Table 9 - Color-Coded Key for Zoning

After individual components were becoming clearer, the overall design of FIDO started to shift and change in order to fit the new changes into the piece. Figure 20 below shows the overall design of FIDO, when elevation and rotation were two different systems and the pinwheel assembly was still loading the tennis balls to the launcher. The total height of this assembly was 22 in. and the base had a diameter of 28 in. The overall housing was a dome structure planned to be made out of fiberglass; however, not pursued due to difficulty in manufacturing.

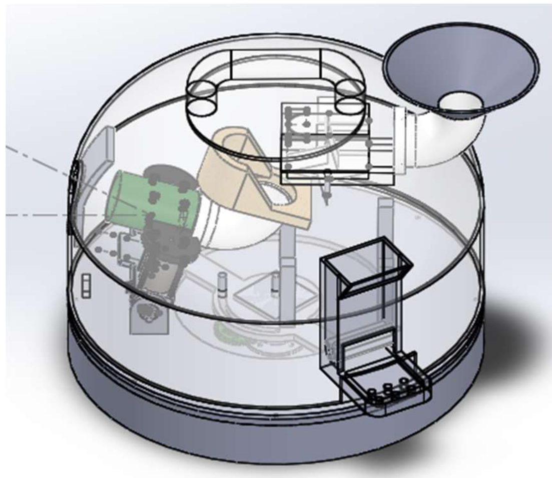


Figure 20 - Overall Design of the First Iteration of FIDO 2.0

After figuring out a way to combine both the elevation and rotation systems into one single aiming system, FIDO had to be redesigned. Figure 21 below reflects those changes to the design. The total height of this assembly was 22 in. and the base had a length of 22 in. and a width of 22 in. The total weight was approximately 38 pounds. The design incorporated a double decker look to provide a platform for the pinwheel assembly to mount on. The vertical distance from the pinwheel to the launcher was 12.5 in. and the horizontal distance from the opening hole to the pinwheel was 15.2 in.

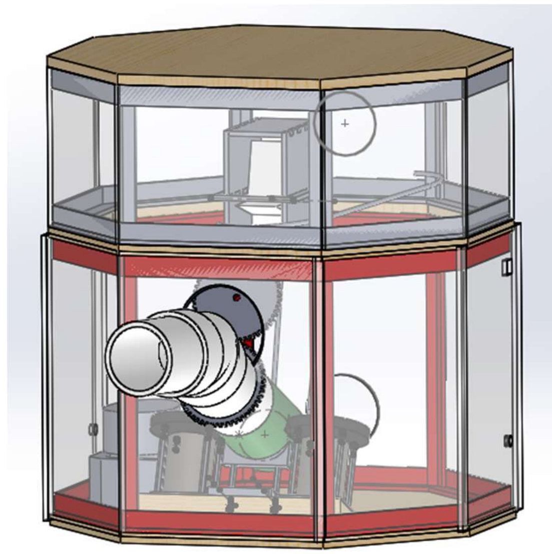


Figure 21 - Overall Design of the Second Iteration of FIDO 2.0

In order to make the height of FIDO shorter, a redesign of the pinwheel assembly was needed. With a new loading system designed, FIDO had a reduced height of 14 ¼ in. The next chapter outlines the final designs of each component of FIDO 2.0.

Chapter 4: Final Designs

Figure 22 below shows the final SolidWorks model of FIDO. The structure keeps the octagon shape of the previous design iterations, however is much smaller due to the newly implemented loading system. The structure's top has a lock, hinge, and handle to open for easy access inside FIDO for potential maintenance. The side panels alternate between acrylic and birch wood to allow the user to see the operation inside and to provide an aesthetically pleasing surface. The height of the final model was 14 ¼ in. The total length and width of the base was 22 in. The total weight of final model was approximately 35 pounds.

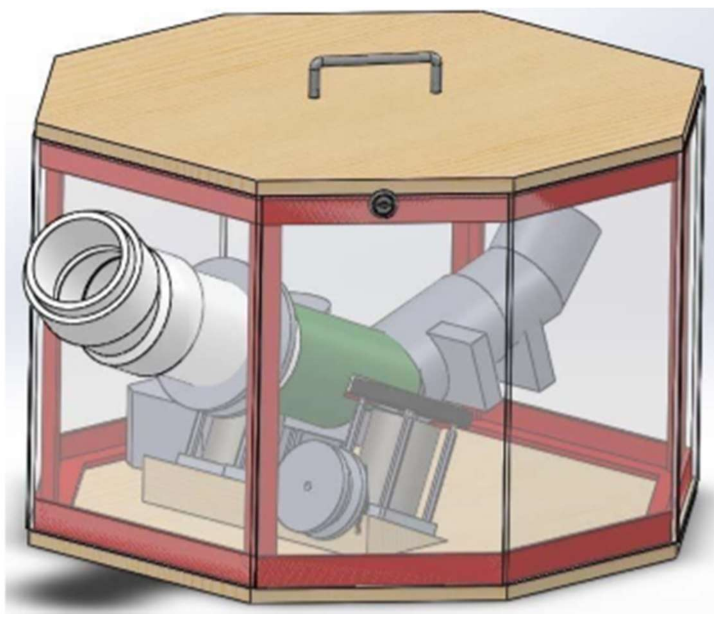


Figure 22 - Overall Design of the Final Iteration of FIDO 2.0

4.1 Launching

In the final design for the launching system, the dual rotating disk design was implemented with slight modifications to the placement of various components. The new launching system as seen in Figure 23 below was placed on a 22.5° plywood ramp made to fit the

¼ in. acrylic plate where the motors were secured. The 3-phase BLDC motors were replaced with new brushed DC motors due to complications on programming the controllers. New acrylic plates were laser cut to secure the new motors in the launching acrylic plate.

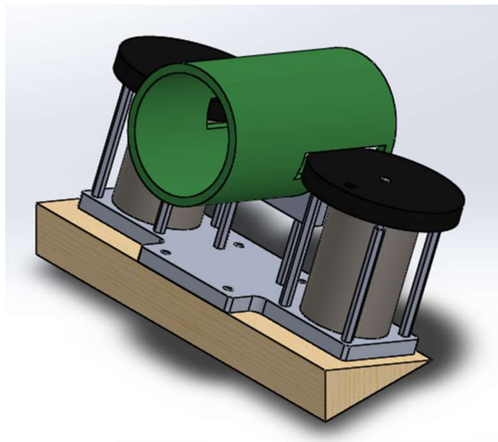


Figure 23 - SolidWorks Model of Launching Component

In order to accomplish a 45° angle for outside operation and 0° for inside usage, a 22.5° PVC pipe elbow was purchase from a local plumbing store. A 2 ½ in. PVC pipe was inserted in one side of the PVC elbow to allow the ball to have an even trajectory surface inside the pipe after leaving the wheels. On the other side of the PVC pipe elbow, a longer PVC piece was cut which connected to the rotating side of the bearing. Roughly 3 in. of free pipe were available for placement of the V-belt guide for aiming. Some other adjustments were displacing the system 2 in. back from its initial position to allow space for a small 22.5° plywood ramp providing good alignment between the pipe and 360° motor.

4.2 Aiming

The final design of aiming incorporates a 6 in. Lazy Susan bearing. One side of the bearing is fixed and attached to the pipe of the launcher. The other side is free to rotate and is attached to a PVC pipe with a 22.5° elbow fitting on the end of it. Since the whole component is angled at 22.5° with the ramp of the launcher, the elbow pipe has a maximum output of 45° and a minimum output of 0° when rotated.

Around the pipe is a 3D printed collar that fits with a V-belt used to rotate the pipe. This collar was printed on a Form 1+ 3D printer. The Form 1+ is a Stereolithographic (SLA) style printer which cures a liquid resin material layer by layer until the part is created. The material that was used for V-Belt collar was called Tough material which is made by Formlabs. Tough material is similar to SMMA (Styrene Methlmethacrylate). A full comparison is shown in Table 10. This material was used for its strength compared to other 3D printing material. It is also one of the few materials which yields rather than shatters when a high level of stress is applied.

	SMMA (Styrene methylmethacrylate)[9]	Tough Resin	Method
Mechanical Properties			
Young's Modulus (10^6 psi)	0.334 – 0.363	0.325	ASTM D638
Yield Strength (ksi)	5.22 – 6.25	7.570	ASTM D638
Elongation	20% - 40%	31%	ASTM D638
Flexural Properties			
Flexural Modulus (10^6 psi)	0.319 – 0.363	0.168	ASTM D790
Impact Properties			
Notched IZOD @ 23°C (ft-lb/in)	0.3612 – 0.3984	0.96	ASTM D256
Thermal Properties			
Heat Deflection @ 66 psi (°F)	199 - 210	109.8	ASTM D648

[8] All values were obtained via the CES EduPack 2015 Software for PMMA (molding and extrusion)
[9] All values were obtained via the CES EduPack 2015 Software for SMMA (clarity, semi-tough)

Table 10 - Material Properties Comparison

Figure 24 - Front View of Aiming Component

The belt is driven by a pulley compatible with V-belts. The pulley is driven by a 360° servo to achieve the desired motion of rotation and position placement. To increase the tension in the belt, an idler was added that could vary in height to increase or loosen tension at will. The pulley, motor and idler are all on a 22.5° ramp to account for the angled launcher and pipe. Figure 24 above shows the front view of the aiming component complete with pulley, belt, and idler.

4.3 Loading

Figure 25 - Top View of Loading Component

The loading mechanism to the wheels is composed of a 3D printed piece created in SolidWorks and a 180° servo motor. The 3D printed model had three parts which made the entire model. One of the parts printed was designed with the intent of capturing the ball and then transferred from the receiving end to the launcher wheels. This part is shaped like a “u” which has a curvature equal to that of a tennis ball. This also prevents the other balls from continuing into the launcher. A shaft combined with a servo coupler was used to control the movements of this particular printed piece. Due to the servos ability to operate between 0° and 180°, a code was written to rotate the “u” to 135° to load the tennis ball. At that position, the infrared sensor would detect an obstruction and go into a function to rotate 90° to feed the ball into the wheels. Figure 25 above shows the complete loading assembly complete with the 3D printed loader, servo motor, and infrared sensor.

4.4 Motor Selection

After redesigning and settling on a final design for each component, it was decided on these types of motors for each of these different applications. The selection of motors can be seen in Table 11.

Application	Motor Type
Launching	Single Phase Brushed DC
Aiming	360° Servo
Loading	180° Servo

Table 11 - Final Motor Selections

Single phase brushed DC motors were used for launching instead of the 3-phase brushless DC motors due to the difficulty of programming and the current draw from those motors. The 3-phase motors required a tele-op controller to manually control the speed and direction of the motors. Since FIDO is an autonomous fetching device, manual control motors would be no good. Two 12V, 6.55oz-in, 4680 rpm brushed DC motors were bought from RobotShop as they are simple and effective motors.

Figure 26 - 360° Sail Winch Servo Motor with Pulley

For aiming, a 360° Sail Winch Servo was used to drive the pulley (as shown in Figure 26), thus rotating the launching pipe. A servo was used in order to have the pipe position known from the internal feedback sensor inside the servo. This allowed the pipe to reach the exact position chosen regardless of the pipes starting position.

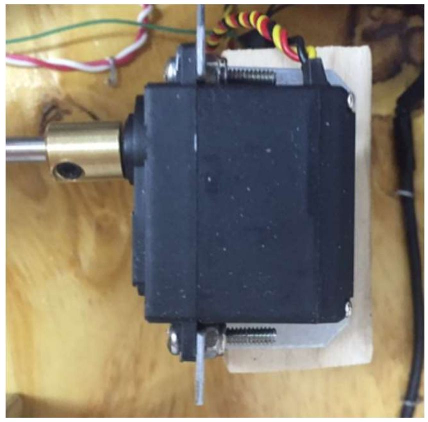


Figure 27 - 180° Servo

For loading, a 180° Servo was used (as seen in Figure 27) to drive the loader piece inserting tennis balls to the launcher. This standard size servo was used because the loader needed to alternate between 45° and 135°.

Chapter 5: Construction and Testing

5.1 Launcher Motor Mount

The launcher motor mount was fully built and assembled. Two caster wheels from Home Depot and two motor hubs from ServoCity.com were purchased to fit cleanly with the motors. However, the diameter of the axle hole of the wheels and the shaft diameter were not compatible. This cause misaligned when connecting the motor mounts to them. To prevent this, a motor mounting alignment tool was designed and 3D printed using the Dimension SST 1200es printer. The piece was a single shaft with two different diameters size, ⅜ in. and ¼ in. The ⅜ in. diameter fit the axle diameter of the wheel and the other fit the motor mount diameter. The printed tool can be seen in Figure 28 below. By using the tool, a greater precision alignment was achieved. When inserting the tool into the wheel and hub, four screw holes with diameter 6/32 in. were drilled in the wheel maintaining a constant wheel alignment while rotating.

Figure 28 - 3D Printed Motor Alignment Tool

After connecting the motor hubs to the wheels, the acrylic motor mounting plates were attached to the DC motor. After attaching the plates, the wheels were mounted to the two motors. The finished attachment can be seen in Figure 29 below.

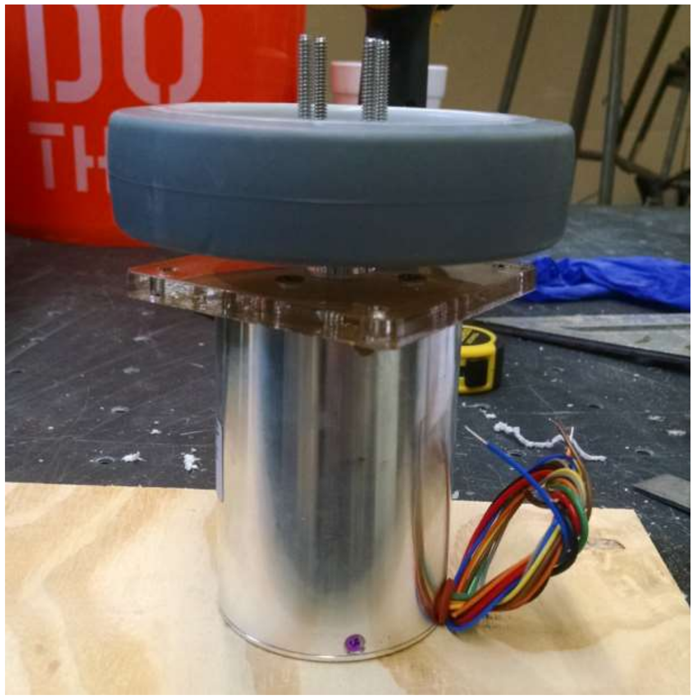


Figure 29 - Aligned Wheel Mounted on Motor

Once the motors were attached, the launcher base could be worked on next. Two pieces of pine wood were cut to fit the curvature of the PVC pipe for the launcher, and then screwed to two male-female standoffs. The standoffs were attached to the acrylic loader base with fitted screws. The assembly of these components can be seen in Figure 30 below. The two motor mounts were able to be attached to the launcher base using eight male-female standoffs (four to each motor).

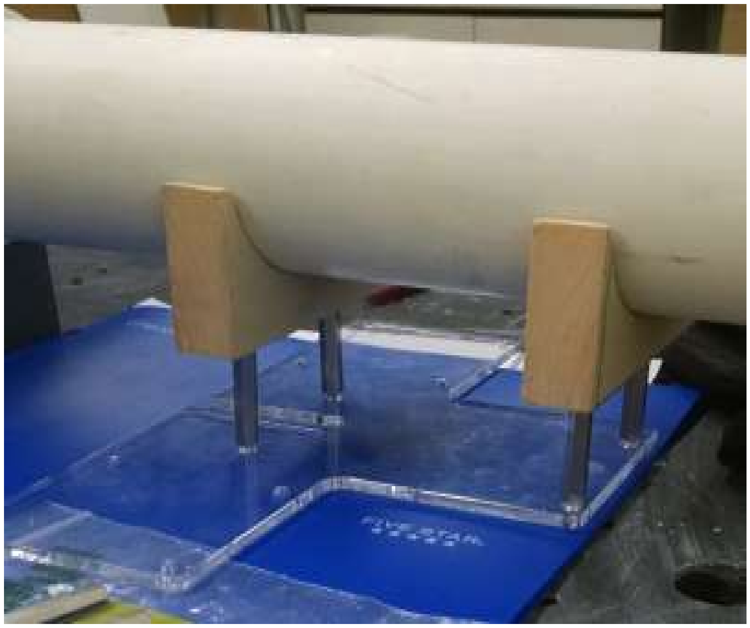


Figure 30 - Pine Wood Pipe Supports

To achieve the desired effect of having the launcher at 22.5°, a 22.5° ramp was created from the horizontal to mount the motor on. Using pine wood to cut the two angled ramp pieces and a rectangle plywood board as the mount, the launcher assembly was fully assembled. The dimensions of the plywood piece were 9 ¼ in. x 4 in. x ¼ in. The ramp and the launcher mount can be seen in Figure 31 below. A PVC pipe was cut to have two slits for the wheels to fit in. While physically testing for contact between the wheels and ball, it was noticed that the wheels weren't making contact with the tennis ball. After taking some measurements it was found that there was an existing gap of ¼ in. Purchasing 3 in. vacuum belts at a local store solved the problem. With the thickness of a single belt equaling ⅛ in., the gap was sealed. After placing the belt onto the wheel, the second test confirmed contact between both wheels with the tennis ball.

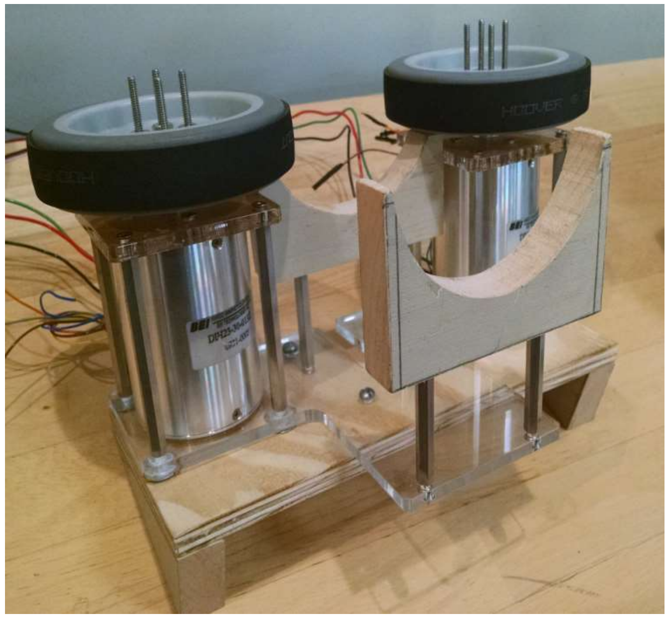


Figure 31 - Launcher System Assembly

Tests were performed by using test code that performed the functions used for both inside and outside operations. These test included testing for the optimal duty cycle for both inside and outside operations, testing the launch distance of the tennis ball for both inside and outside operations, and testing the rpm of the motors with load (wheels) and no load (no wheels) conditions.

5.2 3D Printed Loader

The overall height of FIDO 2.0 decreased significantly with the removal of the pinwheel assembly loader. A new design was implemented in the system that was able to hold a tennis ball with a rocker and then release it to the launcher via servo motor. The assembly is comprised of three separate pieces. The ball enters the elbow pipe at 45° as momentum pushes it through the horizontal piece where it is stopped by the rocker with its launcher end extending inside the pipe. When the sensor reads that an object is present in the loader, the servo motor driving the rocker will rotate about 90° propelling the tennis ball into the spinning wheels of the launcher, thus launching the tennis ball. The elbow pipe has an outside and inside diameter of 2.95 in and 2.7 in, respectfully. The horizontal pipe has an outside and inside diameter of 3.21 in and 2.96 in, respectfully. This allows the elbow pipe to fit cleanly inside the horizontal pipe with no interference as the tennis ball rolls through. The rocker's curvature fits the curvature of the tennis ball like a glove. A SolidWorks model of the design can be seen in Figure 32 below.

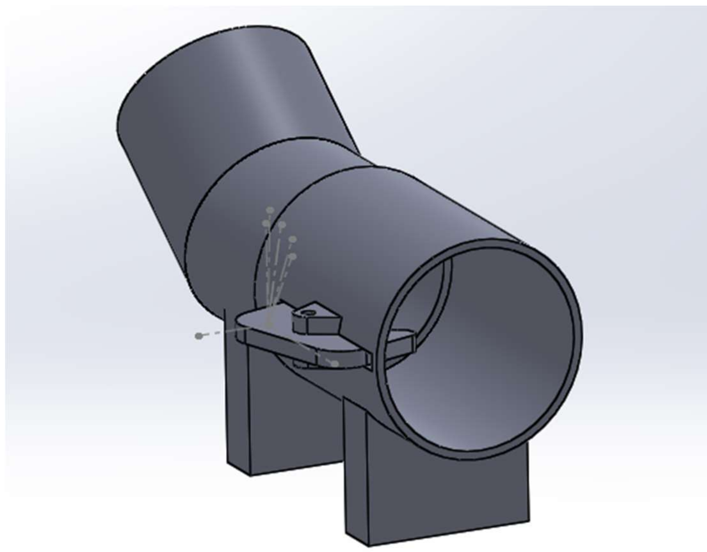


Figure 32 - SolidWorks Model of Loader

In order to create this piece, the Rapid Prototyping laboratory at WPI was consulted to 3D print the pieces using the Dimension SST 1200es printer. The loader came in four pieces, as seen in Figure 33 below.

Figure 33 - 3D Printed Parts for Loader

Using super glue to connect the two slanted pipes together to achieve the elbow shape, we assembled the pieces together to finish the final product, as seen in Figure 34 below. After testing, the loader will be mounted at an angle of 15° from the horizontal to give the tennis balls a constant push downward.

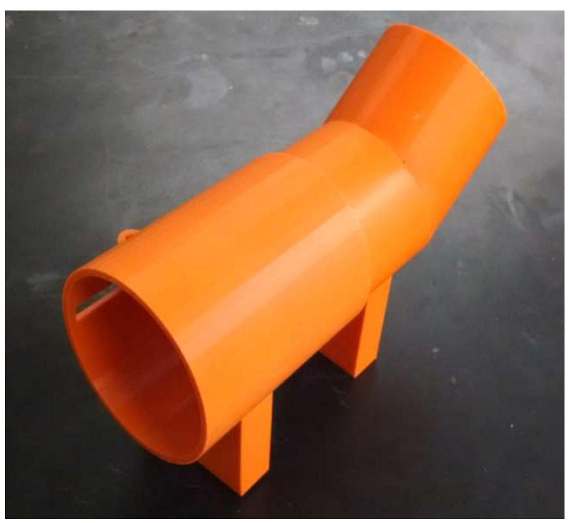


Figure 34 - 3D Printed Loader Assembled

Shaft and servo couplers were ordered from SparkFun Electronics. The servo coupler connects the 180° servo motor to the shaft to achieve smooth operation of the loader. A hole was milled out of one side of the pipe to fit an infrared sensor inside it. The infrared sensor is used to sense if a ball is inside the loader. If a ball breaks the connection of the sensor, a function in the code tells the servo to load the ball into the launcher. Tests were performed using the loader and its components. These tests include having the rocker load a tennis ball from the receiving end to the launching end efficiently, having the singularity effect of the loader work (one ball loaded at a time), and having the infrared sensor sense if the ball is in the loader or not.

5.3 Aiming Assembly

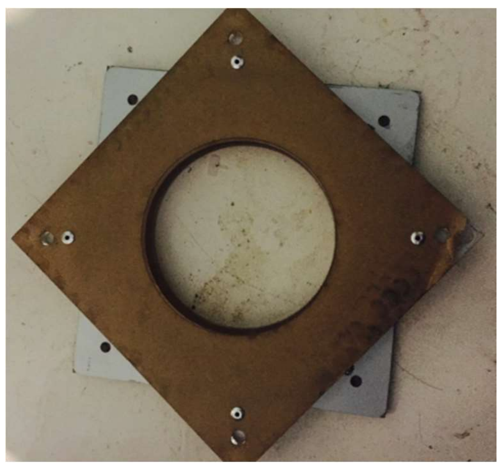


Figure 35 - Front View of Lazy Susan Bearing with Acrylic Plates

The attachment of two 6 in. by 6 in. pieces of ¼ in. acrylic to the Lazy Susan bearing was used for rotation purposes of the PVC pipe. The two pieces were laser cut using a VLS460 Laser Cutter with a 3 ½ in. circle to provide entrance for both PVC pipes. During the building, an existing PVC pipe was used for alignment of both acrylic plates. Once the pieces were aligned, ¼ in. holes were drilled through the acrylic and metal plates for the rivets. The final assembly can be seen in Figure 35.

Once the part was assembled, the determined spacing between both pipes was chosen to be ⅛ in. The overall distance from one acrylic side to the other was 13/16 in. To accomplish the ⅛ in. spacing between both pipes, both pipes would need to be inserted 5/16 in. in each individual acrylic piece. After inserting both pipes into the acrylic piece, a couple tests provided the desired results; the Lazy Susan bearing required minimal effort to overcome friction. A servo motor was still suitable for the application of turning the pipe for the programmable degrees of 0°, 45°, 90°, 180°, and 360° based on the low friction. This assembly can be seen in Figure 36.

Figure 36 - Rotating PVC Pipe Assembly

After some research, a V-belt was chosen as the desired belt for operation. After the belt was chosen, a 3D guide for the belt was designed with the design intent of preventing the belt from slipping horizontally along the PVC pipe. The guide was composed of two printed pieces. The pieces were connected using a 1 ½ in. 6-32 screw with a lock nut. The 3D printed guide can be seen in Figure 37.

Figure 37 - 3D Printed Guide for Belt

The motor chosen for the rotation mechanism was a 360° servo motor. The operation voltage is 4.8V to 6.0V and the motor had capabilities to be control and programmed through the Raspberry Pi. The reasoning behind the selection was based on the fact that the motor would rotate to the desired angle even if the position was accidently physically changed by a user. The 360° servo was tested for inside and outside usage. The average time for the servo to accomplish either position was 6 seconds.

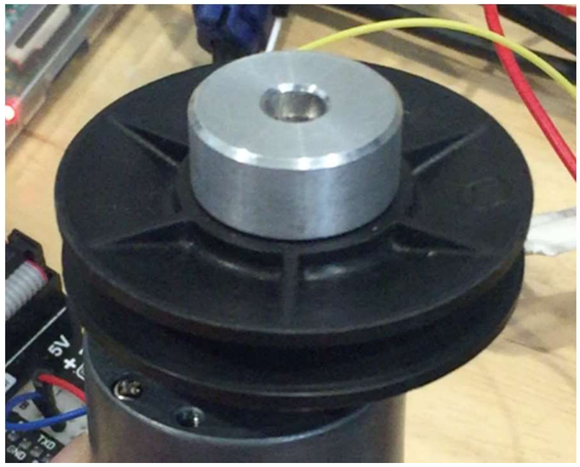


Figure 38 - Pulley Mounted on a DC Motor for Testing

A 2L V-belt and pulley for fractional horsepower motors were chosen due to quiet operations between the pulley and belt, easy installation and removal, and providing a longer life (3-5 years) for the belt. For testing, the pulley is mounted on a low RPM DC motor which would drive the belt and turn the pipe to the desire output angle (0°, 90°, 180°, 270°), as seen in Figure 38.

Figure 39 - Idler for Belt Tension

Figure 39 above shows the idler used for increasing the tension of the belt. The piece is made out of a cylindrical aluminum stock that is glued inside a bearing to allow the stock to rotate without friction. The whole assembly is able to raise or lower height with the help of a lead screw. As the piece rises, the tension of the belt increases allowing better grip and better results rotating the pipe. If the belt needs to be replaced, unscrew the lead screw to lower the height to easily slip the belt out and replace it.

5.4 Housing

Figure 40 - Octagon Weld with Plywood Base

The initial structure was made using 1 in. Hot-Rolled Weldable Steel Solid Angle. Two sides of the octagon were given 10 in. for the input and output usage while another two sides of octagon were given 8 in. The structure base was built in the shape of an octagon with a height of 6 in. to provide enough clearance for the drill battery. A plywood base was attached to the structure once it was sand-downed, primed, and painted red. The half structure weighted more than expected, so options to cut down on the weight were explored. A rebuild of the same shape structure with ½ in. Hot-Rolled Weldable Steel Solid Angle was pursued. Figure 40 shown above is the new redesign bottom frame of the structure being prepared for welding. The new structure was designed with a width of 22 in. and length of 22 in. To maximize the amount of space inside the octagon, the two 8 in. sides were increase to 10 in.

Another adjustment was to the design a single stage storage unit of 14 in. rather than two stages to simplify the design and reduce the assembly time. Once the entire structure was welded, the steel was cleaned up and two coats of rust prevention primer were applied. Once the primer was dry, two coats of a dark red spray paint were applied to resemble WPI's crimson school color.

Two octagonal plywood pieces were cut ¼ in. bigger to account for the ¼ in. acrylic planned to be riveted into the metal frame. Once cut, the pieces were sanded and two coats of semi-gloss varnish were applied. The bottom plywood base was held in place using clamps while ⅛ in. holes were drilled through the wood and steel for the rivets to fit in. On the second plywood piece, a handle was aligned and place in the center of the octagonal cut piece. A lock and hinge were also added to the second plywood base since its design intent was to be used as a door to access the internal components of FIDO. A small wire was placed in the opposite side of the handle to maintain the door open for maintenance purposes, as seen in Figure 41.

Figure 41 - Open Top Plate for Maintenance

The housing was completed using ¼ in. birch wood and ¼ in. acrylic which were laser cut at the Washburn Shops. The four birch wood pieces were cut with the dimensions of 13 ⅝ in. x 8 ½ in. while the four acrylic sheets were cut to the dimension of 13 ⅝ in. x 10 in. A varnish coat was added to the four birch wood pieces once they were riveted into the frame. After installing all the panels, a clear sealant was applied to close the gaps in between the corners of the octagon.

5.5 Sensors and Electronics

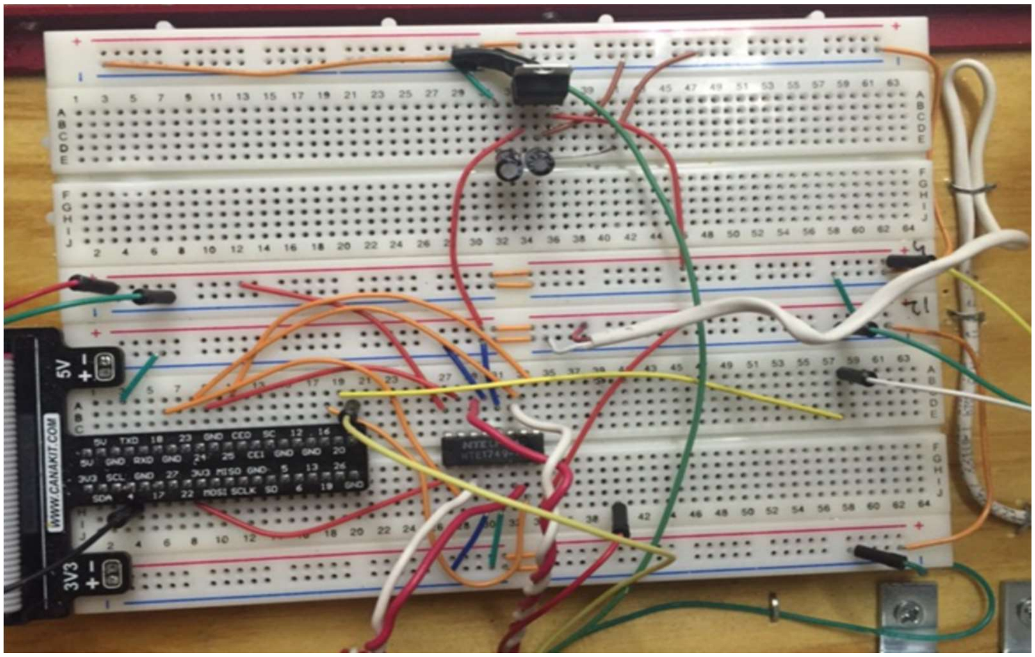


Figure 42 - Breadboard with Electrical Connections

Determining the positioning of the aiming assembly when the device was in use without the use of an encoder proved to be a challenge. It is incredibly difficult to determine the position at all times without the use of expensive electrical components; such as sensors, for example. Resistive wire was explored to determine the position. The resistive wire would act like a variable resistor so every angle would have a corresponding voltage. This would give you a relative position based on the resistivity of the wire per inch. This solution proved to be a little more difficult to implement, purely because the resistivity per inch of the wire was really low This would mean that a large length of wire would be needed to measure any noticeable change in resistance. Another solution that was considered was to use a series of infrared sensors that would transmit different information. These transmitters would be placed at major degree angles; 0°, 90°, 180°, and 270°. A receiver would be placed on the non-moving parts to receive the different information from the transmitter. This would tell the device at what major angle the rotating pipe was at. It would then rotate at a constant speed to achieve the desired angle needed.

```
# Proximity Sensor Test

import RPi.GPIO as GPIO
import time

GPIO.setmode(GPIO.BCM)
GPIO.setup(21, GPIO.IN, pull_up_down=GPIO.PUD_DOWN)

def ProximitySensor(self):
    if GPIO.input(21):     # if port 21 == 1
        print ("Path Block..Wating for Clerance") #Rising edge detected 1
        return True
    else:                  # if port 21 != 1
        print ("Path Clean.. Preparing Motors")  #Falling edge detected 0
        return False


GPIO.add_event_detect(21, GPIO.FALLING, callback=ProximitySensor, bouncetime=200)
```

Figure 43 - Proximity Sensor Test Code

In the previous version of FIDO, the group results provided that the PIR sensor only provided HIGH readings. Figure 43 above shows a while loop which was created to check the operations of the PIR sensor only. After many trials, the results obtained provided both HIGH and LOW readings. However, the sensor feedback was not accurate as the signal would alternate between HIGH and LOW periodically. Specifications on the sensor could be found in Appendix A.

```python
# Port a default status of 0/LOW/False.
GPIO.setup(17, GPIO.IN, pull_up_down=GPIO.PUD_DOWN)

#GPIO.setup(21, GPIO.IN, pull_up_down=GPIO.PUD_DOWN)

def loadISR(self):
    print("Im Inside the function")
    while GPIO.input(17) == 1:
        if GPIO.input(17) == 0:              # if port 17 == 1
            print ("Ball Not Detected")      # Rising edge detected on 17
            pLoad.ChangeDutyCycle(0)
            dog = True
        else:                                # if port 17 != 1
            print ("Ball Detected")          #Falling edge detected on 17
            pLoad.ChangeDutyCycle(10)        #135 degrees to recieve ball
            time.sleep(2)
            print("feeding")
            pLoad.ChangeDutyCycle(5)         #45 degrees to feed ball into launcher
            time.sleep(10)
            pLoad.ChangeDutyCycle(7.5)
            # count += 1
            # return count


GPIO.add_event_detect(17, GPIO.FALLING, callback=loadISR, bouncetime=300)
```

Figure 44 - Infrared Sensor Test Code

Figure 44 shows a test code used to test the Infrared Proximity Sensor Short Range with the implementation of the 180° servo motor. It is important to note that the interrupt event was triggered as soon as the sensor would change state, thus setting the code to GPIO.Falling. When the ball was not detected, the servo was grounded to prevent damage to the inside gear train of the servo. When the ball was detected, the servo was prompt to change the duty cycle to 10 to load a ball and another change in the duty cycle of 5 to feed into the wheels. By changing the duty cycle to 7.5, the servo was allowed to return to its neutral position of 90°.

5.6 Trial Codes Used

5.6.1 PWM DC Motor Test Code

Code Used to Test out the PWM speed variation of the DC Motors:

```
# The Original Code was taken from an online Source
# The code was modified by Arthur to see how the set frequency affected the motor speed

import RPi.GPIO as GPIO    # Get the basic Raspberry Pi active
from time import sleep

GPIO.setmode(GPIO.BCM)
Motor1A = 18
Motor1B = 16
Motor1E = 22
GPIO.setup(Motor1A,GPIO.OUT)
GPIO.setup(Motor1B,GPIO.OUT)
GPIO.setup(Motor1E,GPIO.OUT)

GPIO.output(Motor1E, GPIO.HIGH)
GPIO.output(Motor1A, GPIO.HIGH)
GPIO.output(Motor1B, GPIO.LOW)
p = GPIO.PWM(Motor1E, 50)

p.start(0)

try:
    while True:
        for i in range(100):
            p.ChangeDutyCycle(i)
            sleep(0.02)
        for i in range(100):
            p.ChangeDutyCycle(100-i)
            sleep(0.02)

except KeyboardInterrupt:
    pass

p.stop()
GPIO.cleanup()
```

5.6.2 Servo Motor Test Code

```
## Code Modified by : Hector Rivas
## Origin of Code: Youtube User Upload
## Objective of the code is to be capable of turning between 45 degrees - 135 degrees
## The code will run using PWM
## Time is in seconds

import RPi.GPIO as GPIO
import time

BCMPIN = 4
keyboardInterupt = "CTL+C"
GPIO.setmode(GPIO.BCM)
GPIO.setwarnings(False)

GPIO.setup(BCMPIN, GPIO.OUT)

p = GPIO.PWM(4,50)   #50HZ pulses every second

p.start(7.5) # Neutral position to not allow balls to pass by

try:
    while True:
        p.ChangeDutyCycle(10) # 135 degrees to receive the ball (Initial Position)
        time.sleep(5)
        p.ChangeDutyCycle(5)  # 45 degrees to feed the ball into launcher
        time.sleep(10)
        p.ChangeDutyCycle(7.5) # 90 degrees to receive the ball (Ending Position)
        time.sleep(5)
        p.ChangeDutyCycle(0)  # Grounding the signal
        time.sleep(10)


except keyboardInterupt: #CTL+C or Delete
    p.ChangeDutyCycle(7.5)
    GPIO.cleanup  # release any resources your script may be using.

## Results:
## The standard size servo motor was capable of successfully achieving the desired angles
```

5.6.3 DIH-23-30-013z Motor Test Code

```
# Authors: Hector Rivas & Arthur Fulgoni
# Objective of the code is to run one of the BLDC motors at their specify frequenze
# The motors will be run using PWM
# times is in seconds
import RPi.GPIO as GPIO
import time
GPIO.setwarnings(False)

Pin = 4
keyboardInterupt = "CTL+C"

GPIO.setmode(GPIO.BCM)
GPIO.setup(Pin, GPIO.OUT)

p = GPIO.PWM(Pin,50)
time.sleep(10)

try:
    while True:
      p.ChangeDutyCycle(10)
      time.sleep(5)
      p.ChangeDutyCycle(70)
      time.sleep(5)
       p.ChangeFrequency(100)

except keyboardInterupt:  #CTL+C or Delete
    GPIO.cleanup
```

Chapter 6: Results

6.1 Launching Testing Results

The first tests that were conducted were to test the rpm of the motors with no load (meaning no wheels on the motor) and with load (wheels on the motor) to see how much the load affected the rpm of the wheels. To test this, the rpm was measured with a Digital LED Laser Tachometer Engine Handheld rpm Gauge. The duty cycle was varied for both conditions: load and no load. Figure 45 below shows the results from these tests. The wheels decreased the rpm of the motors by an average of 1500 rpm. For inside, a 25% duty cycle was chosen because it was the minimum duty cycle required to run the motors. For outside, a 65% duty cycle was chosen due to it being the highest rpm that could be achieved without the drawbacks of noise and longer motor operation time. These two duty cycles proved to be the optimal for their specific operation.

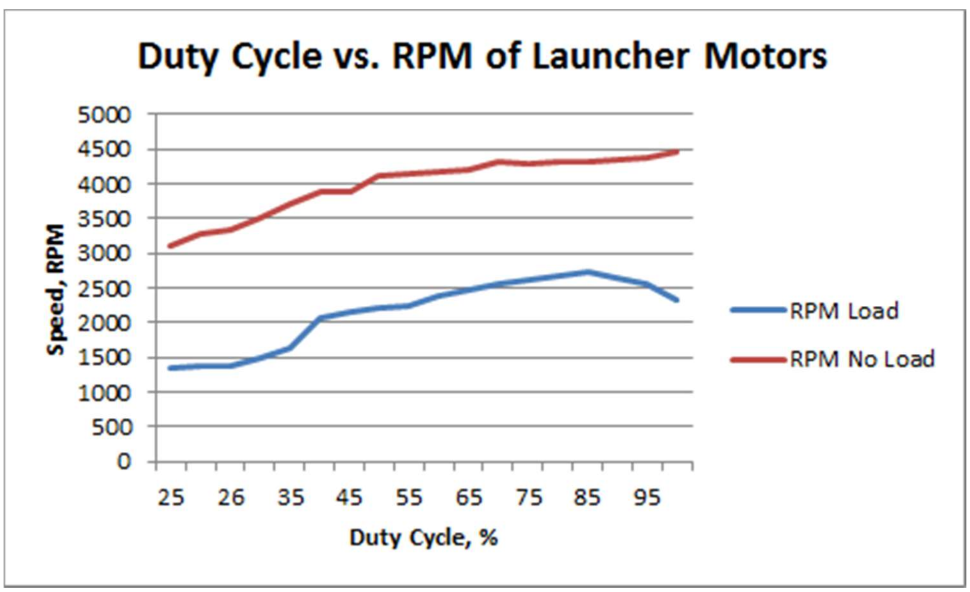


Figure 45 - Duty Cycle vs. RPM of Launcher Motors

The first tests conducted for launch distance provided poor results due to the tennis ball not being sufficiently compressed by the wheels. The starting diameter for the wheels were 4 in. plus the ⅛ in. of the vacuum belt. The first couple of results provided a traveling distance of 1 ft. with the nozzle set to 0° and an average of 4 ft. while the nozzle was adjusted manually to 45°. A distance of 8 ft. was reached during a trial without the nozzle. After performing more trials, it became noticeable that by changing the path of the ball in a tube where the ball had roughly ¼ in. of free space to move vertically reduce the amount of momentum the ball had initially after exiting the rotating wheels. It is important to know that while these trials were being conducted the frequency was set to 500Hz and the duty cycles for the inside and outside settings were set to 25% duty cycle and 65% duty cycle respectively.

During another set of trials, the frequency was set to 1000Hz. At the initial frequency, both motors would speed up to the recorded peak rpm of roughly 2600, but after a few seconds one of the motors would slowly decrease its rpm to a stop. Once the first motor completely stopped, the second motor rpm would slowly decrease while the first motor rpm would start to rise again. After a couple of sessions of alternating high and low motor rpms, both motors would completely stop operating while the programing was still executing commands. At the new frequency, the rpm of the motors was not affected and provided noticeably more power as confirmed by the ball traveling an average of 8 in. more than previous.

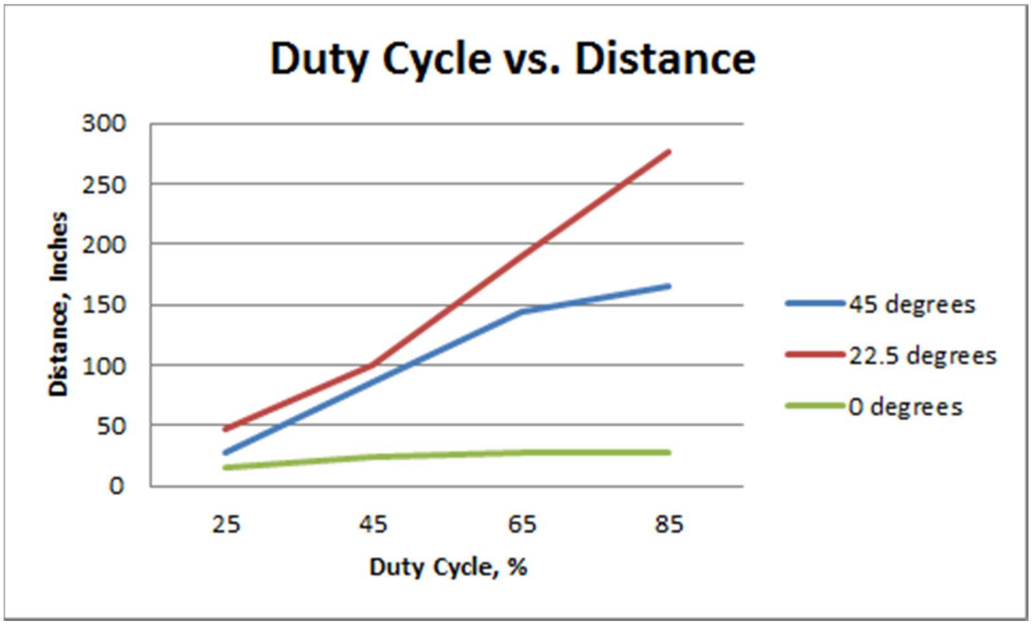


Figure 46 - Duty Cycle vs. Distance

During the last trials, the frequency was set to 2000Hz. Figure 46 above displays the results from these trials. The distance without the nozzle improved from 14 ft. to 23 ft. at the new frequency. However, the distance with the nozzle at 45° maxed at 165 in., or 13 ft. ¾ in. Although not as far with a nozzle, the device still achieved the distance repeatability of the original FIDO, which had a range of 10-15 ft. The strange alternation in rpm between both motors was not seen with this frequency.

6.2 Aiming Testing Results

The aiming mechanism was only tested for 0° and 180° through the usage of PWM. After conducting many trials, both inside and outside positions were successfully performed by the motor. The time recorded for the servo to reach each position was roughly 10 seconds. Due to a lack of belt tensioning and friction between the belt guide screw supports, moving the pipe to the desired positions proved to be difficult. Slippage in the pulley attached to the motor was noticed due to the lack of tensioning. Alignment between the belt guide and motor was another factor that did not allow the pipe to rotate as desired in most of the trials performed. To fix the alignments, two pieces of thin aluminum were added to the ramp supports containing the motor and idler. The idler, which was screwed into the ramp next to the motor, was used to regulate the tension within the belt by unscrewing a nut and adjusting the height manually. To accommodate for the friction in the belt guide, some of the material was filed off from the screws supports allowing enough space for the belt.

6.3 Loading Testing Results

The test performed for the loading system provided satisfying results. Through the usage of the interrupt sequence, the servo successfully rotated to 135° to collect the tennis ball, and after receiving the go ahead from the infrared sensor, successfully rotated to 45° to feed the ball into the wheels. The main commands for controlling the servo were placed inside the LoadISR function of code located in Appendix B. The function was constantly being accessed by the interrupt sequence and the desired tasks were performed depending on the state of the sensor: 0 or 1. 0 meant that the loader was empty and had no tennis balls to launch, while 1 meant that a tennis ball has interrupted the sensor and is ready to be loaded.

6.4 Control Systems Testing

FIDO 2.0 PIR sensor was tested for HIGH and LOW signals through the Raspberry Pi. However, the sensor signals would periodically alternate without placing any objects directly in front or around the sensor. The signal alternation between HIGH and LOW affected the motors directly since they would speed up when nothing was detected in the path (LOW) and stop when the PIR sensor reported a blockage to the Raspberry Pi (HIGH). The proximity sensor was not part of the final working prototype; however, locations were chosen for placement on the structure. The first location was attaching it below the nozzle at a distance of 1 ½ in. and second location was on either side of the nozzle at the same distance of 1 ½ in.

The infrared sensor used for the loading application successfully executed the task of loading and feeding the tennis ball once the sharp proximity sensor detected the ball. Implementing the load sensor into the final code was successfully done and tests were run to prove the program worked as desired. As the launch motors were running, once a ball was inserted into the loader, the sensor would trip and load the ball successfully into the launcher wheels.

6.4 Power Supply Testing

The 12V Milwaukee battery was salvaged from the original FIDO. Initially, FIDO's entire electrical system was to be operated through this battery. A Tw0 linear 5 Voltage divider was purchased from the SparkFun website to drop the battery voltage to 5V, supplying enough voltage for the Raspberry Pi to operate. After testing the linear divider output voltage, the correct output voltage was achieved; however, during every test the Pi would turn on for a few seconds then immediately shut down. A separate 6V battery pack to power up the Raspberry Pi was implemented and solved the problem.

It was decided to keep the voltage divider in the circuit board to provide a constant supply of 5V to run motors whose operating voltage ranged between 4.8-6.0V. FIDO 2.0 provides a switch for the user to control turning the RPi on and off. The 12V Milwaukee battery supplied 12V to the motors directly. Trials of singular motors were performed using the battery pack source without encountering any issues.

Figure 47 - IEC 320 C6 Connector

FIDO 2.0 implemented an IEC 320 C6 Connector (Figure 47) soldered into the battery charging station and riveted in the same acrylic sheet which the switch was located, as shown in Figure 48 below.

Figure 48 - Side panel with Switch and Battery

Chapter 7: Conclusions and Recommendations

The designs and motors for each key component of FIDO 2.0 have been chosen to perform a desirable task. The new version of FIDO provides faster operations and reduction in the overall footprint, as well as in weight. The height was reduced from 30 in. to 14 ¼ in. and 4 in. were shaved off from the length and width of the base. FIDO 2.0 has an output range of 0°-45°. FIDO 2.0 can load and launch a tennis ball in 15-20 seconds. The smaller frame combined with the handle on the top plate makes FIDO 2.0 portable from indoors to outdoors. The hinged top plate makes for easy access to the inner components of FIDO 2.0 which allows for easier maintenance. The octagon shaped, red painted frame with alternating acrylic and birch wood side plates make for a more aesthetically pleasing design.

Based on the results of this report, the following conclusions can be drawn. The rotation and elevation system should be redesigned without the need of the nozzle. Remove both 22.5° ramps and design a mechanical system to raise and lower the entire launching plate from 0° to 45° while not compromising the height of FIDO 2.0. The conclusions of eliminating the nozzle were derived from the last trials in which the tennis ball was able to achieve a maximum distance of 23 ft. with no nozzle and a launch angle of 22.5°, while the farthest distance reached from the 45° nozzle was 13 ft. ¾ in. A possible suggestion would be to add a sling vertical launcher wheel. This would guide the ball around a ramp and fire it out of the device. By changing the rpm, different distances would be achievable.

The implementation of the in-stock touchscreen would be highly advised for future iterations to provide visual control of the device. Explore the Tkinter library in Python to program a user friendly interface in which the number of launching times could be set up, the environment setting, a time interval for treats, and desired input motor rpms. The interface could be created to fit the entire screen and the buttons links to the respective destination. In addition, add speakers with set voice recordings to keep the dog both engaged and entertained with the device.

Another recommendation would be to transform FIDO into a device that zoo animals could interact and engage with. With its bulky, sturdy design, FIDO could easily transform into a device that could play with zoo animals without fear of destruction from the animals. This would alleviate a common problem in zoos where the animals are just so bored that they just sit around and do nothing, which in turn makes watching those animals a sad experience. FIDO can solve those problems by having the animal be more engaged by playing fetch with them, which in turn will make watching those animals a fun and happy experience. This does not mean to scrap the domestic dog market, but instead have two different products. One product for domestic dogs that is a bit smaller and capable for indoor play and storage, and another product for zoo animals that is larger and bulkier and capable for the inevitable abuse that a wild animal will give it.

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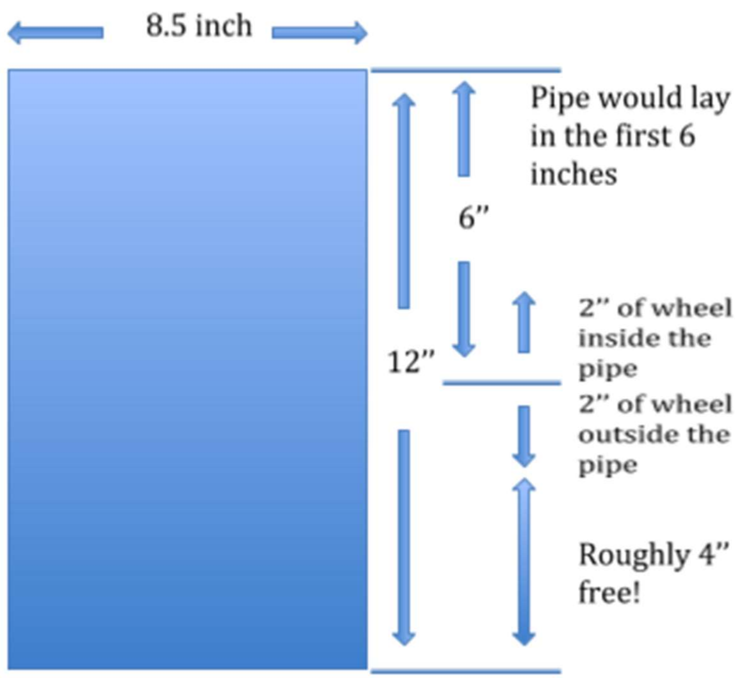
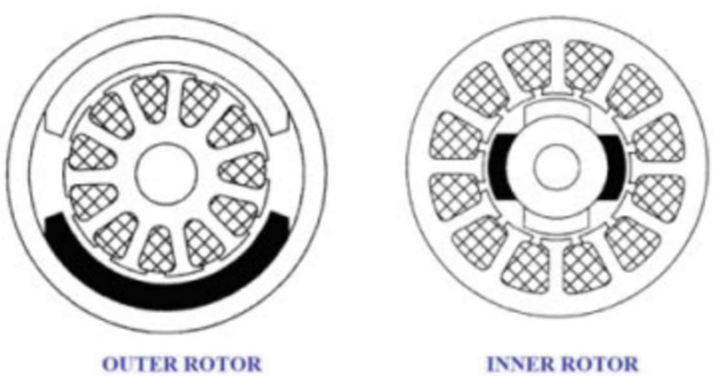
Appendix A: Components Used

Dimensions to the initial Elevation Plate

Wheel Diameter: 3" ~ 4"
Ball Diameter = 2.5"
Elevation Base Material: Light Metal, or wood

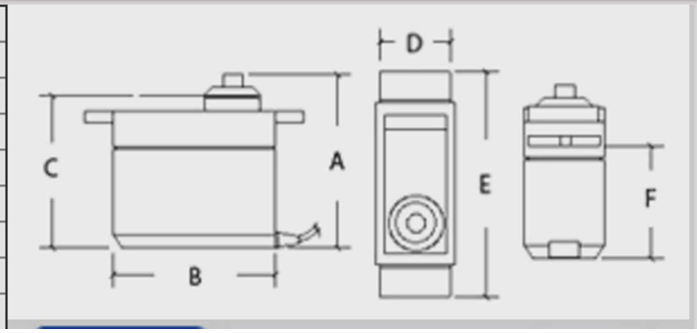


BLDC Motor Configurations



Sail Winch Servo 13kg / 0.7sec (360deg) / 55g dimensions

Weight (g)	55
Torque (kg)	13
Speed(Sec/60deg)	0.7
A(mm)	44
B(mm)	41
C(mm)	40
D(mm)	20
E(mm)	58
F(mm)	27



Sail Winch Servo 13kg / 0.7sec (360deg) / 55g Specifications

Weight: 55g

Dimensions: 40.5 x 20.2 x 38mm

Speed: 0.9sec / 360deg (4.8v) - 0.7sec / 360deg (6.0v)

Torque: 11kg.cm (4.8v) - 13kg.com (6.0v)

Operating voltage: 4.8 - 6.0V

Gear train: Metal

HS-625MG 180° Servo Motor

Detailed Specifications

Control System: +Pulse Width Control 1500usec Neutral
Required Pulse: 3-5 Volt Peak to Peak Square Wave
Operating Voltage: 4.8-6.0 Volts
Operating Temperature Range: -20 to +60 Degree C
Operating Speed (4.8V): **0.18sec/60° at no load**
Operating Speed (6.0V): **0.15sec/60° at no load**
Stall Torque (4.8V): **76.37 oz/in. (5.5kg.cm)**
Stall Torque (6.0V): **94.43 oz/in. (6.8kg.cm)**
Operating Angle: 45 Deg. one side pulse traveling 450usec
Continuous Rotation Modifiable: Yes
Direction: Clockwise/Pulse Traveling 1500 to 1900usec
Current Drain (4.8V): 8.8mA/idle and 400mA no load operating
Current Drain (6.0V): 9.1mA/idle and 500mA no load operating
Dead Band Width: 8usec
Motor Type: 3 Pole Ferrite
Potentiometer Drive: Indirect Drive
Bearing Type: Dual Ball Bearing
Gear Type: 3 Metal Gears and 1 Resin Metal Gear
Connector Wire Length: 11.81" (300mm)
Dimensions: 1.59" x 0.77"x 1.48" (40.6 x 19.8 x 37.8mm)
Weight: 1.94oz. (55.2g)

Additional Information:

PWM = 1500 - servo does not rotate.

PWM > 1500 - servo rotates clockwise continuously.

More PWM value - more rotation rate.

PWM < 1500 - servo rotates counterclockwise

3 Phase Brushless DC motor

- Smooth, quiet, high torque brushless DC motor
- 2 ¼'' Diameter by 3.0'' long
- ¼'' Diameter by 1'' long shaft
- 5270 RPM with no load
- Built in speed sensor
- 7-15V DC operating voltage

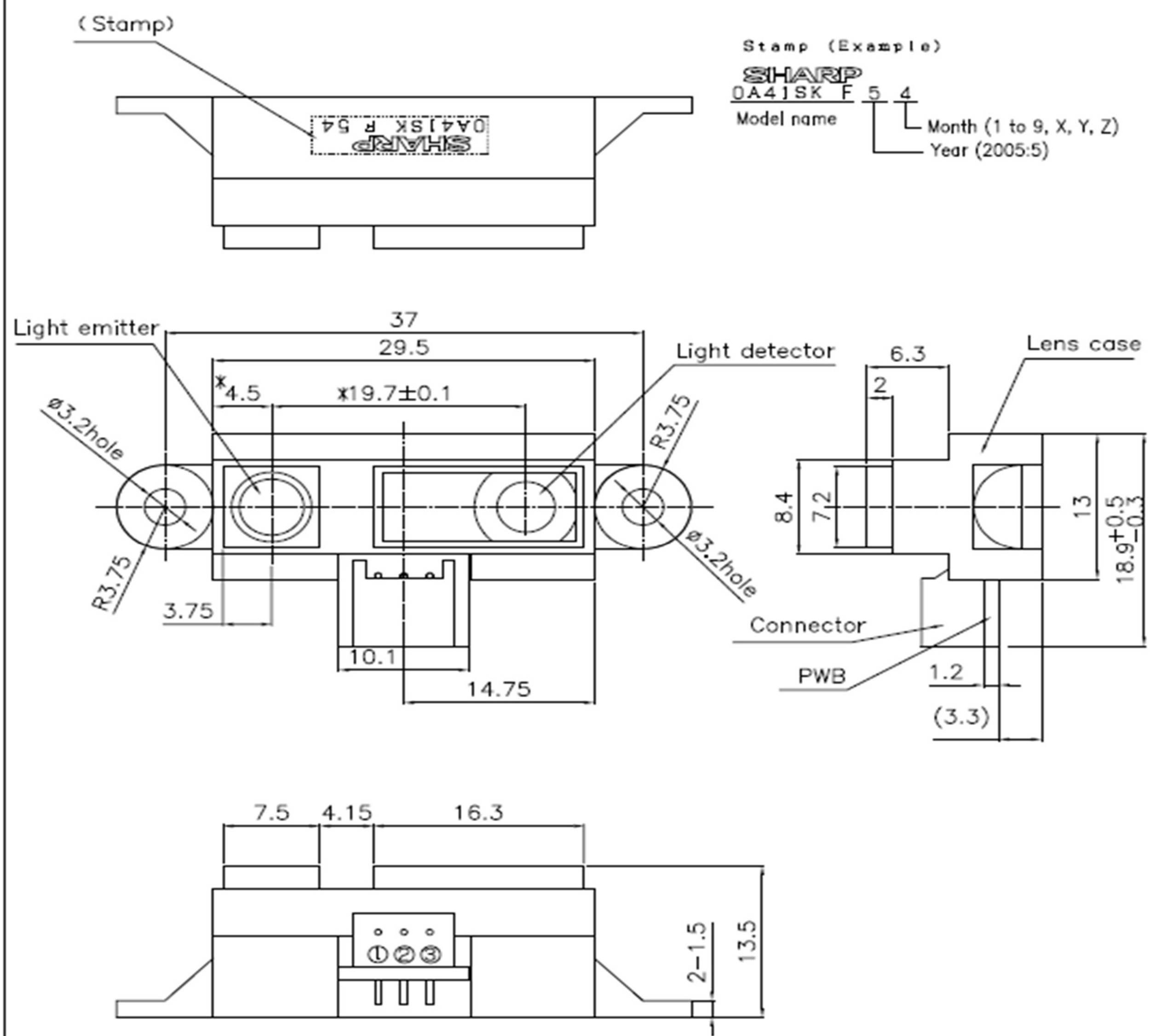
Infrared Proximity Sensor Short Range - Sharp GP2Y0A41SK0F

- Distance measuring sensor is united with PSD, infrared LED and signal processing circuit
- 2. Short measuring cycle (16.5ms)
- 3. Distance measuring range : 4 to 30 cm
- Package size (29.5 × 13.0 × 13.5mm) 5. Analog output type

Absolute Maximum Ratings

(Ta=25°C, Vcc=5V) Parameter	Symbol	Ratings	Unit	Remark
Supply voltage	Vcc	-0.3 to +7	V	-
Output terminal voltage	Vo	-0.3 to Vcc+0.3	V	-
Operating temperature	Topr	-10 to +60	°C	-
Storage temperature	Tstg	-40 to +70	°C	-

Infrared Proximity Sensor Short Range - Sharp GP2Y0A41SK0F - Outline



Connector signal

	Signal name
①	Vo
②	GND
③	Vcc

Connector :
J.S.T.TRADING COMPANY,LTD.
S3B−PH

Materials
Lens: Acrylic acid resin
(Visible light cut−off resin)
Case: Carbonic ABS
(Conducttive resin)
PCB: Paper phenol

Unit: mm   Scale: 2/1

Note 1: The dimensions marked * are described the dimensions of lens center position.
Note 2: Unspecified tolerance shall be ±0.3mm.
Note 3: The dimensions in parenthesis are shown for reference.

Name	GP2Y0A41SK0F Outline Dimensions
Drawing No.	CY13044j 02

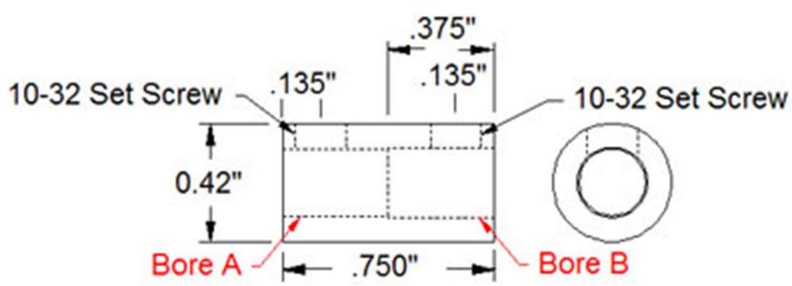
Servo Shaft Coupler - Hitec Standard

- Length - 0.5”
- Outer Diameter - 0.42”
- Inner Diameter - 0.25”
- C1 Hitec Spline

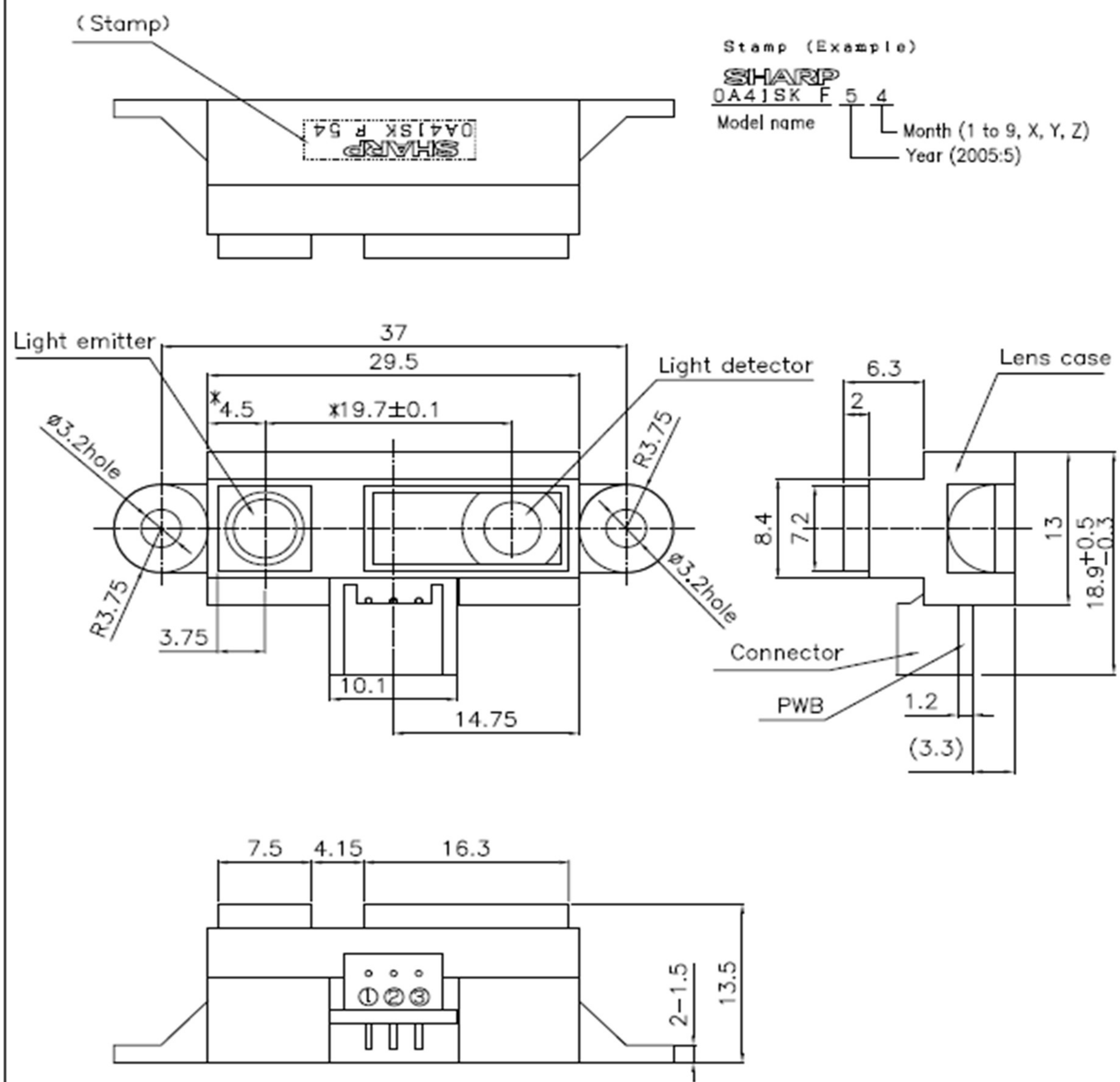
Infrared Proximity Sensor Long Range - Sharp GP2Y0A02YK0F

- Distance measuring range: 20 to 150 cm
- Analog output type
- Package size: 29.5×13×21.6 mm
- Consumption current: Typ. 33 mA
- Supply voltage : 4.5 to 5.5 V

Set screw shaft coupler



Infrared Proximity Sensor Long Range - Sharp GP2Y0A02YK0F - Outline



Connector signal

	Signal name
①	Vo
②	GND
③	Vcc

Connector :
J.S.T.TRADING COMPANY,LTD.
S3B−PH

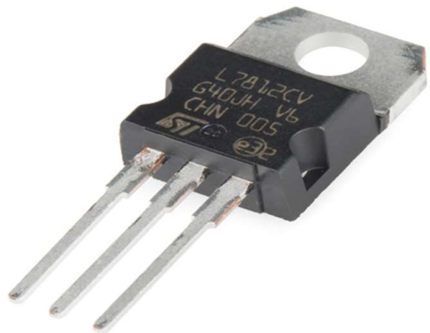
Materials
Lens: Acrylic acid resin
(Visible light cut−off resin)
Case: Carbonic ABS
(Conducttive resin)
PCB: Paper phenol

Unit: mm Scale: 2/1

Note 1: The dimensions marked * are described the dimensions of lens center position.
Note 2: Unspecified tolerance shall be ±0.3mm.
Note 3: The dimensions in parenthesis are shown for reference.

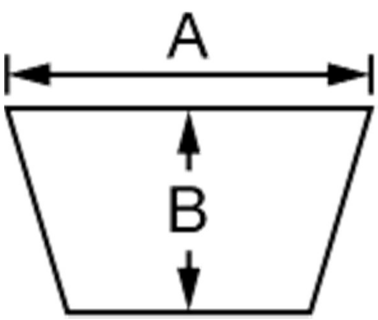
Name	GP2Y0A41SK0F Outline Dimensions
Drawing No.	CY13044j 02

Voltage Regulator - 12V COM-12766 ROHS



- Output current to 1.5A
- Output voltages of 5; 5.2; 6; 8; 8.5; 9; 10; 12; 15; 18; 24V
- Thermal overload protection
- Short circuit protection
- Output transition soa protection

2L-Section V-Belt
Trade Size 2L240, 24" Outer Circle



Section	2L
Trade Size	2L240
Outer Circle	24"
Top Width (A)	1/4"
Height (B)	1/8"
Color	Black
Material	Rubber

4’’ Threaded Stem with Brake Non-Marking Rubber Caster

Stem width (in.)	1.5
Wheel Diameter (in.)	4 in
Wheel Width (in.)	1.25 in

Appendix B: Raspberry Pi Code

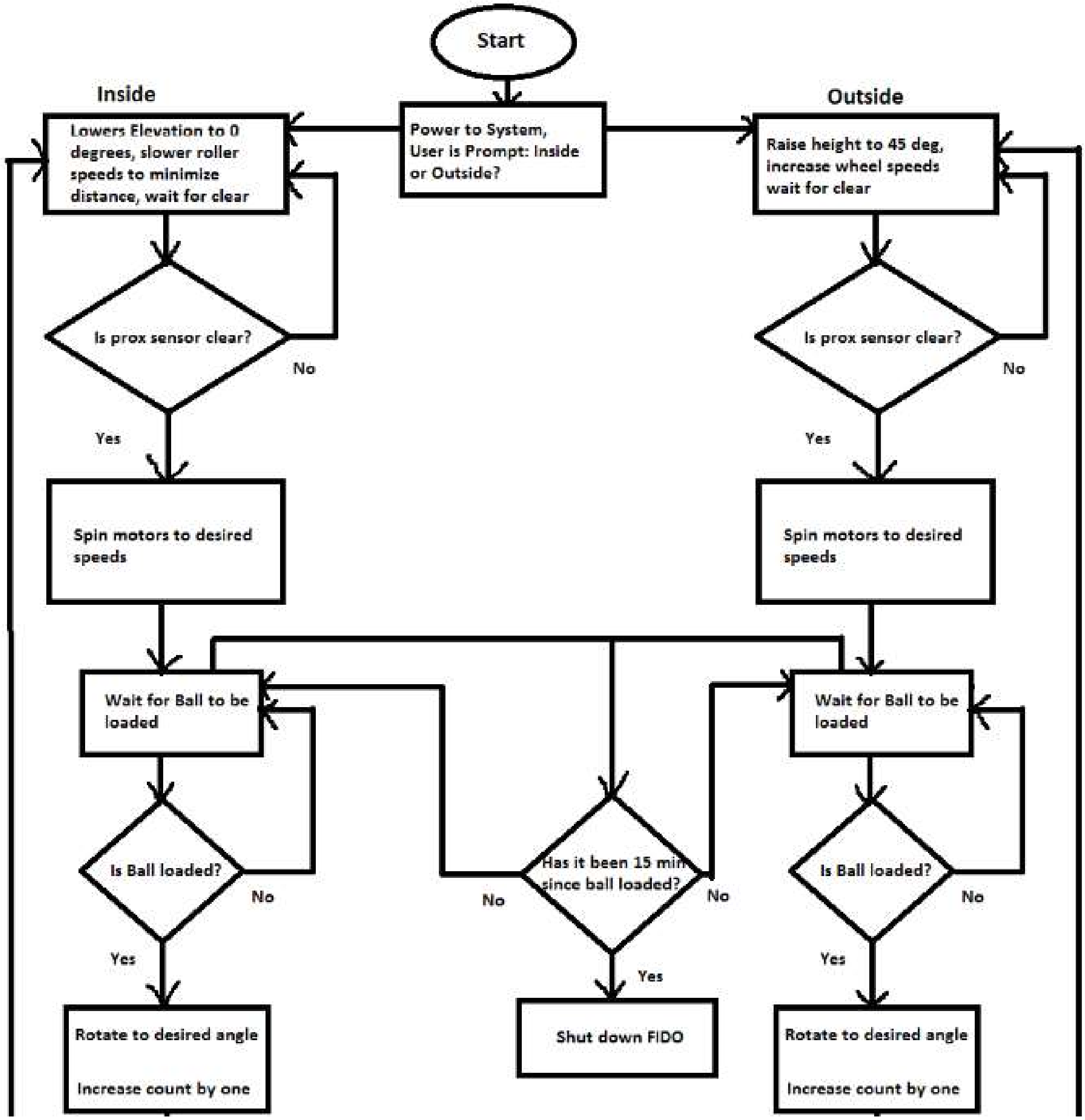
```
## FIDO 2.0V MQP TEST
## Authors: Hector Rivas and Arthur Fulgoni
## Revised: Nick Brown (CS Major) and Jack (RBE Major)

# Setting Up the Raspberry Pi GPIO
import RPi.GPIO as GPIO
import time              # from time import sleep
from threading import Thread

GPIO.setmode(GPIO.BCM)
count = 0
loaded = True


# Interrupt Sequences Pin 17 short Range Proximity Sensor
# Pin 21 Proximity Sensor to stop the motors
GPIO.setup(17, GPIO.IN, pull_up_down=GPIO.PUD_DOWN)
GPIO.setup(21, GPIO.IN, pull_up_down=GPIO.PUD_DOWN)

# Function Used for the Short Range Proximity Sensor
def loadISR(self):
    if GPIO.input(17) == 0:               # if port 17 == 1
        print ("Ball Not Detected")       # Rising edge detected on 17
        pLoad.ChangeDutyCycle(0)

    else:                                  # if port 17 != 1
        print ("Ball Detected")            #Falling edge detected on 17
        pLoad.ChangeDutyCycle(10)          #135 degrees to recieve ball
        time.sleep(20)
        print ("Feeding")
        pLoad.ChangeDutyCycle(5)           #45 degrees to feed ball into launcher
        time.sleep(10)
        print("Returning to loading position")
        pLoad.ChangeDutyCycle(10)
        time.sleep(2)
        pLoad.ChangeDutyCycle(0)


def ProximitySensor():
    global isBlocked
    while True:
        isBlocked = (GPIO.input(21) == 1)
```

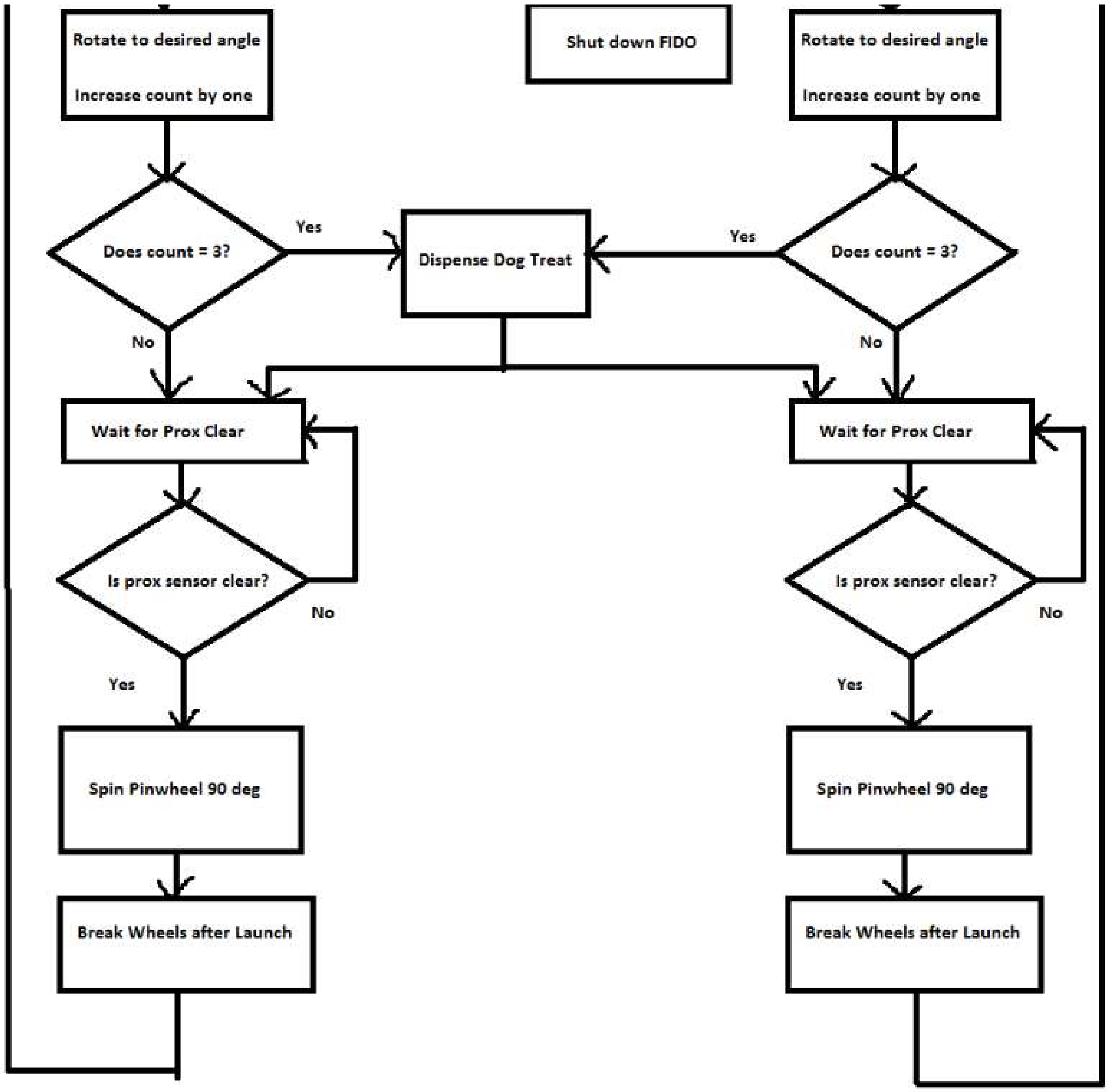
```
# Setting up the thread which will be running the entire time
# The thread was set up and made global for stopping the motors faster
isBlocked = False
proximitySensorThread = Thread(target=ProximitySensor)
proximitySensorThread.start()


# Interupt Sequence for Both ISR sensor and Proximity Sensor.
GPIO.add_event_detect(17, GPIO.FALLING, callback=loadISR, bouncetime=300)

#GPIO.add_event_detect(21, GPIO.FALLING, callback=ProximitySensor, bouncetime=300)

MotorL1A = 16
MotorL1B = 18
MotorL1E = 22


MotorL2A = 23
MotorL2B = 24
MotorL2E = 25

LoadMotor = 13
GPIO.setup(LoadMotor,GPIO.OUT)      #Servo Motor for Loading

pLoad = GPIO.PWM(LoadMotor,50)      #50 Hz pulses per sec

RotMotor = 19
GPIO.setup(RotMotor,GPIO.OUT)       #Servo Motor for Rotation

pRot = GPIO.PWM(RotMotor,50)        #50 Hz pulses per sec


try:
    print('Hello! I am FIDO! Will we be playing Inside or Outside?')
    while True:
        filename = raw_input('')
        if filename == 'Inside':
            print("Excellent choice! I will set my launch pipe to 0 degrees for safe indoor play!")

           GPIO.setup(MotorL1A,GPIO.OUT)       #Launcher DC Motor Right
           GPIO.setup(MotorL1B,GPIO.OUT)
           GPIO.setup(MotorL1E,GPIO.OUT)

           GPIO.setup(MotorL2A,GPIO.OUT)       #Launcher DC Motor Left
           GPIO.setup(MotorL2B,GPIO.OUT)
           GPIO.setup(MotorL2E,GPIO.OUT)

           GPIO.output(MotorL1E, GPIO.HIGH)    #Launcher Motor Right Output
           GPIO.output(MotorL1A, GPIO.HIGH)
           GPIO.output(MotorL1B, GPIO.LOW)

           GPIO.output(MotorL2E, GPIO.HIGH)    #Launcher Motor Left Output
           GPIO.output(MotorL2A, GPIO.LOW)
           GPIO.output(MotorL2B, GPIO.HIGH)

           pLaunch1 = GPIO.PWM(MotorL1E, 2000)
           pLaunch2 = GPIO.PWM(MotorL2E, 2000)
```

```python
        pRot.ChangeDutyCycle(0)

        pLaunch1.start(0)
        pLaunch2.start(0)

        pLoad.start(12.5)

        while True:
            if not isBlocked:
                print("Not blocked")
                pLaunch1.ChangeDutyCycle(65)
                pLaunch2.ChangeDutyCycle(65)
                pLoad.ChangeDutyCycle(10)       #135 degrees to recieve ball

                if loaded == False:
                    print('Feed')
                    pLoad.ChangeDutyCycle(5)    #45 degrees to feed ball into launcher
                    time.sleep(10)
                    pLoad.ChangeDutyCycle(10)
                    print('back to receive')
                    loaded = True
            else:
                print("Block detected")
                pLaunch1.ChangeDutyCycle(0)
                pLaunch2.ChangeDutyCycle(0)


    elif filename == 'Outside':
        print('Fantastic! Ah, the great outdoors! I will set my launch pipe to 45 degrees for exciting outdoor play!')

        GPIO.setup(MotorL1A,GPIO.OUT)       #Launcher DC Motor Right
        GPIO.setup(MotorL1B,GPIO.OUT)
        GPIO.setup(MotorL1E,GPIO.OUT)

        GPIO.setup(MotorL2A,GPIO.OUT)       #Launcher DC Motor Left
        GPIO.setup(MotorL2B,GPIO.OUT)
        GPIO.setup(MotorL2E,GPIO.OUT)

        GPIO.output(MotorL1E, GPIO.HIGH)    #Launcher Motor Right Output
        GPIO.output(MotorL1A, GPIO.HIGH)
        GPIO.output(MotorL1B, GPIO.LOW)

        GPIO.output(MotorL2E, GPIO.HIGH)    #Launcher Motor Left Output
        GPIO.output(MotorL2A, GPIO.LOW)
        GPIO.output(MotorL2B, GPIO.HIGH)

        pLaunch1 = GPIO.PWM(MotorL1E, 2000)
        pLaunch2 = GPIO.PWM(MotorL2E, 2000)

## This section of the code was going to be used to tranfer the code for rotation
## The rotation code was tested independently from the main code

        #pRot.ChangeDutyCycle(0)
        #time.sleep(2)
        #pRot.ChangeDutyCycle(180)

        pLaunch1.start(0)
        pLaunch2.start(0)
        while True:
            pLaunch1.ChangeDutyCycle(95)
            pLaunch2.ChangeDutyCycle(95)

            if loaded == False:
                pLoad.ChangeDutyCycle(10)           #135 degrees to recieve ball
                print('Get ball')
                time.sleep(5)
                pLoad.ChangeDutyCycle(5)            #45 degrees to feed ball into launcher
                print('feed')
                time.sleep(10)
                pLoad.ChangeDutyCycle(7.5)          #90 degrees to recieve ball
                loaded = True
            else:
                pLoad.ChangeDutyCycle(0)            #Grounding the signal
```

```
        else:
            print('I do not understand? Please answer with Inside or Outside! Thank you!')


except:
    pLaunch1.stop()
    pLaunch2.stop()

finally:
    GPIO.cleanup()
```

Appendix C: Flow Chart of Operation




Rotate to desired angle
Increase count by one
Shut down FIDO
Rotate to desired angle
Increase count by one
Does count = 3?
Yes
Dispense Dog Treat
Yes
Does count = 3?
No
No
Wait for Prox Clear
Wait for Prox Clear
Is prox sensor clear?
No
Is prox sensor clear?
No
Yes
Yes
Spin Pinwheel 90 deg
Spin Pinwheel 90 deg
Break Wheels after Launch
Break Wheels after Launch

Appendix D: Motor Selection Calculations

Torque Calculations for Firing Distance

FIDO MQP
9/23/2015

Inputs

$a_x = 0\,\frac{m}{s^2}$ — Acceleration in the x-direction

$a_y := g = 9.8066\,\frac{m}{s^2}$ — Acceleration in the y-direction (acceleration due to gravity)

$\theta := 45°$ — Firing Angle

$x := 50ft$ — Distance to Cover in the X-Direction

$t := 5s$ — Time for wheels to reach speed

$\rho := 1600\,\frac{kg}{m^3}$ — Density of Material (Neylon)

$r := 2in = 0.0508\,m$ — Radius of Wheel

$w := 1.375in = 0.0349\,m$ — Width of Wheel

Calculation for 45 degree

$$v_0 := \sqrt{\frac{g \cdot x^2}{2(\cos(\theta))^2 \cdot \tan(\theta) \cdot x}} = 12.2251\,\frac{m}{s}$$

$$\tau := \frac{\rho \cdot \pi \cdot r^3 \cdot w \cdot v_0}{2 \cdot t} = 0.0281 \cdot N \cdot m$$

Calculation for 30 degree

$\theta_1 := 30°$ Firing Angle

$$v_{01} := \sqrt{\frac{g \cdot x^2}{2(\cos(\theta_1))^2 \cdot \tan(\theta_1) \cdot x}} = 13.1367 \frac{m}{s}$$

$$\tau_1 := \frac{\rho \cdot \pi \cdot r^3 \cdot w \cdot v_{01}}{2 \cdot t} = 0.0302 \cdot N \cdot m$$

Distance Reached with Original Velocity at 30 degrees

$$v_x := v_{01} \cdot \cos(\theta_1) = 11.3767 \frac{m}{s}$$

$$v_y := v_{01} \cdot \sin(\theta_1) = 6.5684 \frac{m}{s}$$

$$t_1 := \frac{v_{01}}{g} = 1.3396 \, s$$

$$x_1 := 0.5 \cdot g \cdot t_1^2 + v_y \cdot t = 41.6407 \, m$$

Given: $a_x = 0\ m/s^2$

$a_y = 9.81\ m/s^2$

$\theta = 45°$

$x = 15.24\ m$

$V_y = \sin(45)\ V_o$

$V_{ox} = \cos(45)\ V_o$

x-direction

$x = V_x t$

$\Rightarrow x = [\cos(45)\ V_o]\ t$

$t = \dfrac{x}{[\cos(45)]\ V_o}$

y-direction

$y = \frac{1}{2} g t^2 + V_{yo} t$

$y = \frac{1}{2} g \left(\dfrac{x}{\cos(45) V_o}\right)^2 + \left(\sin(45)\ V_o\right)\left(\dfrac{x}{\cos(45)\ V_o}\right)$

$y = \dfrac{g x^2}{2(\cos(45))^2\ V_o^2} + \tan(45)\ x$

$$\Rightarrow 0 = \frac{-9.81\ (15.24)^2}{2(\cos(45))^2\ V_o^2} + \tan(45)(15.24)$$

$$-\tan(45)\ (15.24) = -\frac{9.81\ (15.24)^2}{2(\cos 45)^2\ V_o^2}$$

$$V_o = \sqrt{\frac{9.81\ (15.24)^{2}}{2\ (\cos(45))^2\ \tan(45)\ (15.24)}}$$

$V_o = 12.227\ m/s$ No Drag assumption

$$\omega = \frac{V_0}{r}$$

$$\alpha = \frac{\left(\frac{V_0}{r}\right)}{t}$$

$$\tau = J\alpha$$

$$J = \frac{M \cdot r^2}{2} = \frac{\rho V r^2}{2} = \frac{\rho \pi \left(\frac{D^2}{4}\right) r^2 \cdot L}{2} \Rightarrow J = \frac{\left(\rho \pi \left(\frac{D^2}{4}\right) \cdot L\right) \cdot r^2}{2}$$

$$\Rightarrow \tau = \frac{\rho \pi r^3 \cdot L}{2} \frac{V_0}{r \cdot t} = \frac{\rho \pi r^3 \cdot L \cdot V_0}{2 \cdot t}$$