Final Report – Automated Catapult

Brendan Blacklock, IEEE #97835244 (Primary)

Jacob Holyoak

Keegan Kelp

Josiah Ramirez

Texas Tech University

November 2021

Abstract

This design utilizes a Raspberry Pi 4, Python, OpenCV and various electrical components to automate a catapult launch. Python and OpenCV are used to detect the target, calculate the target distance and height, detect target hits, and recalibrate if not hit. To center on the target, a DC motor is used to rotate the catapult. The launch angle of the catapult is adjusted using an 8-inch linear actuator and a MPU6050 accelerometer. The internal firing mechanism is retracted using a 6-inch linear actuator and released by de-energizing an electromagnet; to measure the pull-back force, a S-Beam load cell is used.

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1. Design Introduction

The Raspberry Pi 4 is currently being utilized in conjunction with a Logitech C270 720p camera, Python, and OpenCV to detect the target, calculate the target distance and height, and track the projectile after launch for hit recognition. The GPIO pins of the Raspberry Pi 4 are being manipulated with Python to send and receive the proper signals and interface with the electrical components needed in the design.

To automate the entire launch process, several different systems are needed. The launch angle system utilizes an 8-inch linear actuator and a MPU6050 accelerometer. The MPU6050 accelerometer employs I2C communication to deliver acceleration vectors along the X, Y, and Z-axis. These values are used to determine current launch angle. Current launch angle is then used to retract or extend the 8-inch linear actuator until the value is equal to the desired launch angle for the determined target distance. The firing system uses three important electrical components; these components include a 6-inch linear actuator, a 50 kg S-Beam load cell, and a 130 lb holding force electromagnet. The electromagnet is deployed to connect the inner firing mechanism to the 6-inch linear actuator. The 6-inch linear actuator retracts the inner firing mechanism until the S-Beam load cell reading is equal to the desired force for the current launch; the electromagnet is then de-energized causing the inner firing mechanism to release and launch the projectile. The target centering system employs a 12 V, 5rpm DC motor to rotate the base component left and right to center the launcher on the target. OpenCV, Python, and the Logitech C270 are implemented to find the center of the target, relay the correct turning position to the DC motor, and stop movement when the center of the camera frame is aligned with the center of the target.

2. Design Aspects

This design utilizes the Raspberry Pi 4, Python, and OpenCV to acquire and center on the target, determine target distance and height, and after launch, recognize if the target has been hit. If the target is not centered with the catapult, the catapult scans side-to-side until the target is centered. To hit targets at varying distances and heights, physics equations are implemented to determine launch angle and force. Systems are in place to adjust launch angle and fire at the desired force. If the target is hit, the projectile is launched with the same force and angle. If the target isn't hit but can be found in frame, the position of the projectile is found and launch force and angle are adjusted accordingly. All aspects of this design exhibit the automation capabilities of the Raspberry Pi 4 and will be discussed in further detail.

2.1. Mechanical Aspects of Catapult Design

To achieve all aspects of automation, a special version of a ballista style catapult is used. The design can be simplified into the following components: the launcher component, the support component, and the base component. Each component will be discussed in greater detail (Refer to Appendix A for Design and Prototype Figures).

For the launcher component, a wooden board is used as the base. Secured to the front of this board is a 1.25-inch PVC pipe; this is considered the outer pipe. A tee fitting is secured parallel to the front of the outer pipe to allow for the projectile to be loaded from the top of the fitting. A 1-inch PVC pipe with a perpendicular tee fitting is fed through the outer pipe; this 1-inch pipe is the inner pipe and firing mechanism. The tension force comes from four springs. The springs are attached in pairs to each side of the tee fitting on the inner pipe. From the tee fitting, the springs are secured to the wooden board. The S-Beam load cell is secured at the back end of the wooden board, and the back of the 6-inch linear actuator is attached to the front of the S-Beam load cell. The electromagnet is attached to the front of the linear actuator. On the back of the inner pipe tee fitting, a magnetic metal plate is secured. This plate allows for the electromagnet to attach to, and release from, the firing mechanism.

The support component allows for stability and proper movement of the launcher component when launch angle is adjusted; it consists of two wooden vertical supports with a rail system and a wooden horizontal beam to support the front end of the launcher component and connect the two vertical supports. To properly adjust the launch angle, the front end of the launcher component must be able to move vertically, and the back end must be able to move horizontally. As mentioned, the horizontal support beam is attached to the front end of the launcher component; the vertical rail system allows for the front end to move up and down as the launch angle is adjusted. The 8-inch linear actuator is mounted on the underside of the horizontal support beam, which in turn, will raise and lower the front end of the launcher component. Another rail system is implemented to secure the back end and allow for proper horizontal movement.

The base component is attached to a platform underneath via a Lazy-Susan to allow for swivel movement. A DC motor is secured and dropped through the base component; the shaft of the motor is secured to the platform underneath. This allows for the base component to turn left or right and center the launcher component on the target.

2.2. Raspberry Pi 4, Python, and OpenCV

The Raspberry Pi 4 Model B is a low cost, single-board computer that operates on Raspberry Pi OS, a Linux-based system; the board has 40 general-purpose input/output pins to connect to electrical components. The Raspberry Pi 4 used has 8 GB of RAM and an operating voltage of 5 V. It is recommended to have a power supply with a max output current of 3 A. Most of the electrical components used in this design operate at 12 V DC; therefore, to power the entire system, a 12 V battery with 7 Ah is implemented. To power the Raspberry Pi 4, A DC/DC buck converter is utilized to step-down from 12 V to 5 V with 3 A max output current; the output of the buck converter is wired to a power distribution PCB with USB-A ports. A USB-A to USB-C cable is connected from the PCB to the Raspberry Pi 4 USB-C power port to supply 5 V.

To control the electrical components and acquire target data through the Logitech C270 720p camera, Python and OpenCV are utilized. The Logitech C270 delivers 720p resolution video quality at 30 FPS. Python is a high-level programming language with many unique libraries. NumPy and Imutils are Python libraries implemented to add efficient array and image processing functions; however, the main libraries utilized in this design are OpenCV for image processing and RPi.GPIO for control of the Raspberry Pi 4 GPIO pins. Python scripts utilizing OpenCV are developed to detect and center on the target, and calculate the target distance, height, and projectile position, post-launch.

An image is a matrix of pixel values where the pixel values represent the color of the pixel. To properly detect the target, a section of the image matrix with the same color values as the target are detected. OpenCV stores images and live feed data in the BGR color space; therefore, for better color segmentation, all data is converted to the HSV

(Hue, Saturation, Value) color space. The target is bright green Velcro; therefore, lower, and upper HSV bounds are determined for bright green. Using these HSV bounds, a binary mask is created where all pixels in the bounds are white (1), and all other pixels are black (0). From this mask, the largest contour is found and the (x, y) values and radius of the contour are calculated. A circle is then drawn around the detected target.

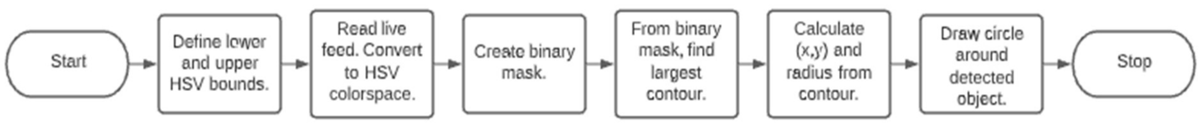


Figure 1: Target Detection Flowchart

After detecting the target, the target distance and height are found to assist in determining the launch angle and force. To determine target distance, the idea of similar

$$Focal\ Length = \frac{(Pixel\ Width * Distance)}{Width} \tag{1}$$

$$Distance = \frac{(Width * Focal\ Length)}{Pixel\ Width} \tag{2}$$

triangles is applied. The following equations demonstrate how the focal length is calculated and then used to determine distance. The focal length is found once by placing the target a known distance away, taking an image, and measuring the width of the target in pixels. Once the pixel width is found, this value along with the known width and distance of the target are used to calculate focal length. This focal length value is then used to determine target distances at varying, future positions. The center of the camera frame remains the same height from the ground; therefore, to find the target height, the difference between the center of the frame and the center of the target is computed and scaled to inches. Then the height of the center of the frame from the ground is added to this calculated height to determine to final height.

After the distance and height have been calculated, and the projectile has been launched, code checks if the projectile hit the target. To accomplish this, multi-object detection is implemented; it follows the same process as the target detection function but creates a secondary binary mask for the projectile. The live feed is read, and the target and projectile are detected. For the launch to be considered a successful hit, the distance between the centroids of the target and projectile must be less than the radius of the target. These values are scaled based on the target distance. If the target was not hit, the launch angle and force are adjusted, and another projectile is launched.

2.3. Launch Angle System

The launch angle system consists of the 8-inch linear actuator and a MPU6050 accelerometer; it allows for the launch angle to be adjusted based on the distance of the target from the catapult. The 8-inch linear actuator has an operating voltage of 12 V DC,

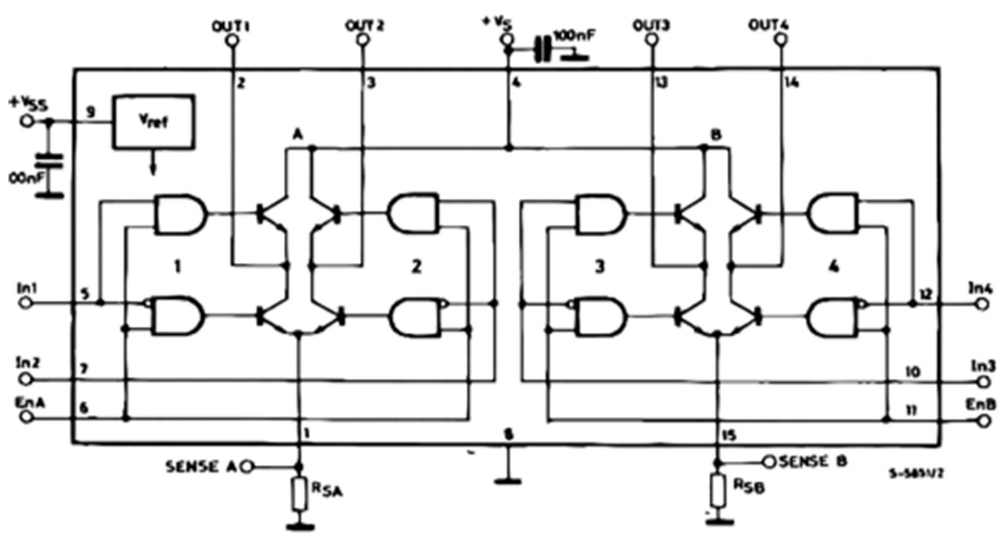


Figure 2: L298 H-Bridge Block Diagram [4]

a max current draw of 3 A, and supports a maximum load of 1000 N. To properly extend and retract the actuator to adjust angle, a L298 dual H-bridge circuit board is used. The L298 is given a supply voltage of 12 V and operates at a current between 0 and 36 mA. The enable and input pins are wired to GPIO pins on the Raspberry Pi 4. To extend the actuator, the enable is driven high, input 1 is driven high, and input 2 is driven low; to retract the actuator, the inputs are reversed. The MPU6050 accelerometer operates at 3.3 V and is mounted to the underside of the launcher component. It has a 16-bit ADC and is wired to GPIO pins of the Raspberry Pi 4. It outputs 8-bit packets containing acceleration vector values along the X, Y, and Z-axis through I2C communication.

A Python script is developed to calculate angle of inclination relative to the X-axis (launch angle) and extend or retract the actuator to achieve the desired launch angle for the calculated target distance. The script reads the raw acceleration vector values,

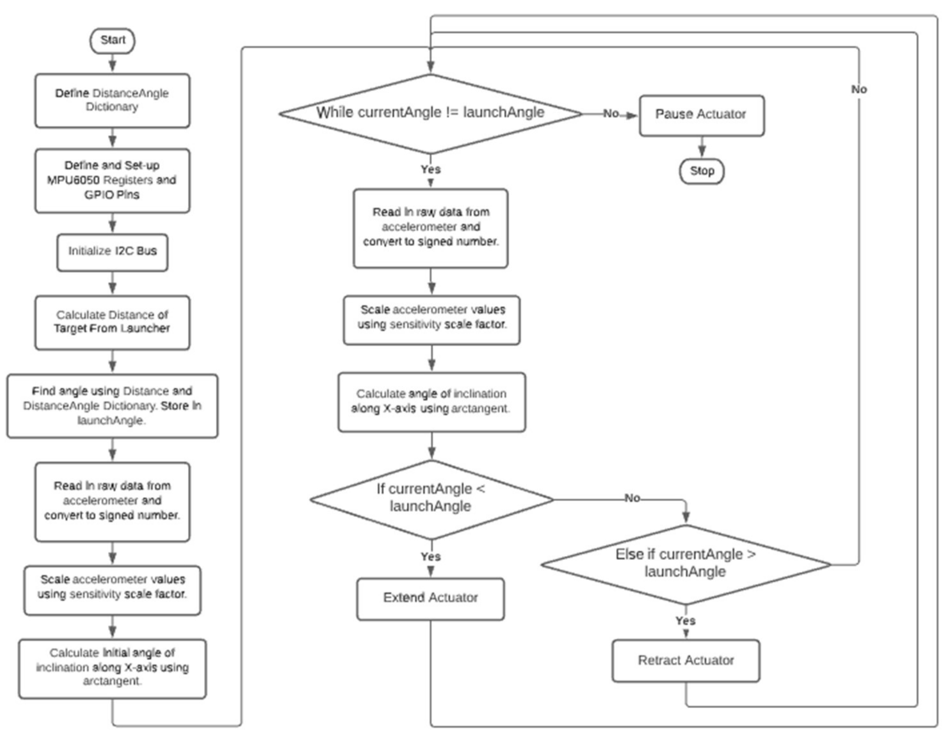


Figure 3: Launch Angle System Flowchart

converts these values from unsigned to signed and scales them using a defined sensitivity value. A right triangle is formed by the gravity vector and the acceleration vectors in the X and Y directions; therefore, the current angle of inclination is found by taking arctangent of the acceleration vector in the X direction over the acceleration vector in the Y direction. An initial reading of the current angle is taken, and while the current angle is not equal to the determined launch angle, a condition checks if the current angle is less or greater than the determined launch angle and extends or retracts the actuator. Once the current angle is equal to the determined launch angle, the linear actuator is paused, and the system moves to the next state.

2.4. Firing System

The firing system employs a 6-inch linear actuator, a 50 kg S-Beam load cell, and a 130 lb holding force electromagnet; it allows for the firing mechanism to be retracted until the desired force is met. The 6-inch linear actuator operates at 12 V DC, has a max current draw of 3 A, and supports a maximum load of 900 N. It is controlled with the second H-bridge on the dual H-bridge circuit board discussed in the launch angle system section. The previously discussed process to extend and retract the 8-inch linear actuator applies to the 6-inch linear actuator as well.

The 50 kg S-Beam load cell measures the push or pull force applied and outputs a small voltage from -3 mV to 3 mV. To accurately read the output signal, the load cell is wired to the HX711 amplifier. The HX711 is supplied a voltage of 5 V, which in turn powers the load cell, and is connected to GPIO pins of the Raspberry Pi 4. The 24-bit ADC of the HX711 allows the output signal to be amplified to a readable, digital signal. To read the force applied in pounds, the first 24-bit number read is stored in a variable sample; this is for calibration purposes. This sample value is then subtracted from the current reading and scaled to represent the value in pounds.

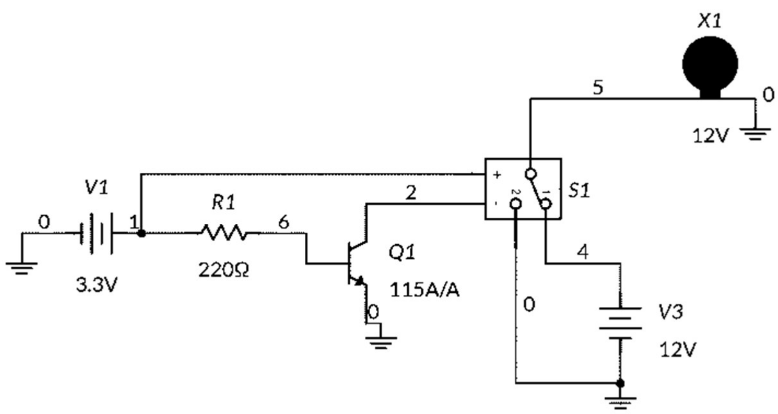


Figure 4: Circuit Schematic for Electromagnet [5]

The 130 lb holding force electromagnet operates at a voltage of 12 V DC; therefore, to energize the magnet, a 2N2222 NPN BJT transistor is used in conjunction with a G5LE-14 SPDT relay. The base of the BJT transistor is wired to a GPIO pin on the Raspberry Pi 4 which outputs 3.3 V. The SPDT relay is also being supplied 3.3 V and 12 V. When a high signal is sent from the Pi, current flows through the transistor, energizes the coil of the relay, and activates the electromagnet.

To properly launch at the desired force for the calculated target distance, a Python script is developed to retract the firing mechanism until the desired launch force is met, and then release the mechanism to fire the projectile. The program begins by checking if the load cell is reading a negative value, if so, we are pushing against the firing mechanism and can energize the electromagnet. Once connected, the 6-inch linear actuator retracts until the load cell reading is equal to the determined launch force. Once the launch force is met, the electromagnet is de-energized, releasing the firing mechanism and launching the projectile.

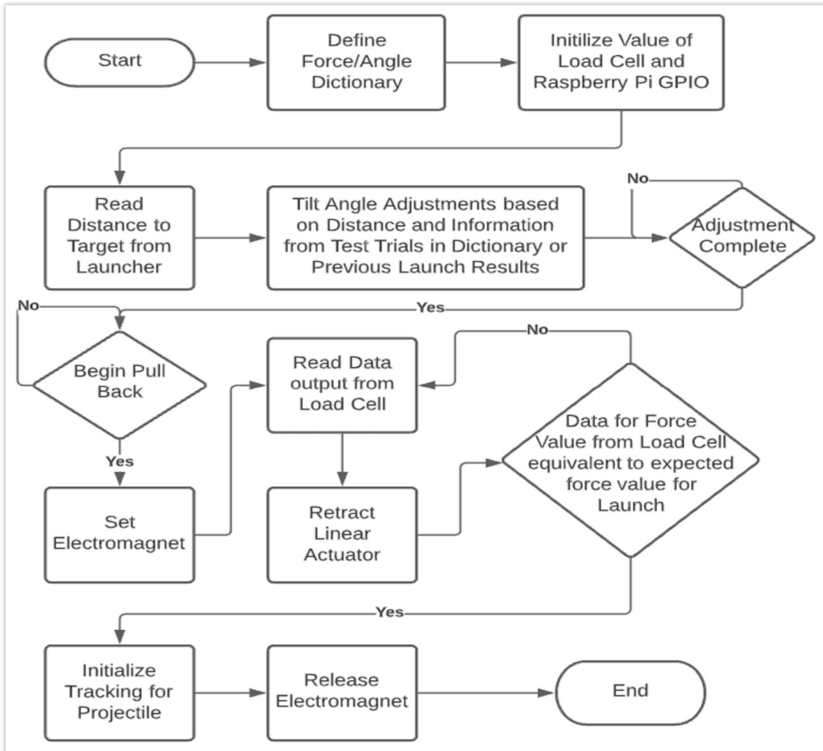


Figure 5: Firing System Flowchart [2]

The launch angle is pulled from a dictionary of values based on target distance while the launch force is calculated using the following physics equations:

$$V = \frac{\Delta x}{\sqrt{\frac{2(\Delta y\left(\cos^2(\theta)\right) - \Delta x \sin(\theta)\cos(\theta)}{g}}} \tag{3}$$

$$Force = (9.5)(1.27)^{Velocity} + 7 \tag{4}$$

After launch, the Python script for hit recognition is implemented to find the projectile in the frame. If the hit was registered, the next projectile is launched at the same angle and force. If the hit was not registered but found in frame, the centroid is calculated and target height is adjusted based on the projectile's height, which in turn, corrects the launch force for the next launch. This process repeats until 2 consecutive hits are registered.

2.5. Target Centering System

The target centering system utilizes a 12 V DC motor, OpenCV, and the Logitech C270 720p camera to align the center of the frame with the center of the target. The DC motor has an operating voltage of 12 V and a rated current of 1.6 A. It rotates at 5 rpm and has a torque of 35 kg/cm. A second H-bridge board is used to control the DC motor. The same process applied to the linear actuator H-bridge circuits, is applied here. To center on the target, the script for target detection is utilized. Once the target is found in frame, the motor inputs are driven to rotate the catapult left or right based on the position of the target in frame. Once the center of the target is aligned with the center of the frame, both motor inputs are driven low, and the system moves to the next state.

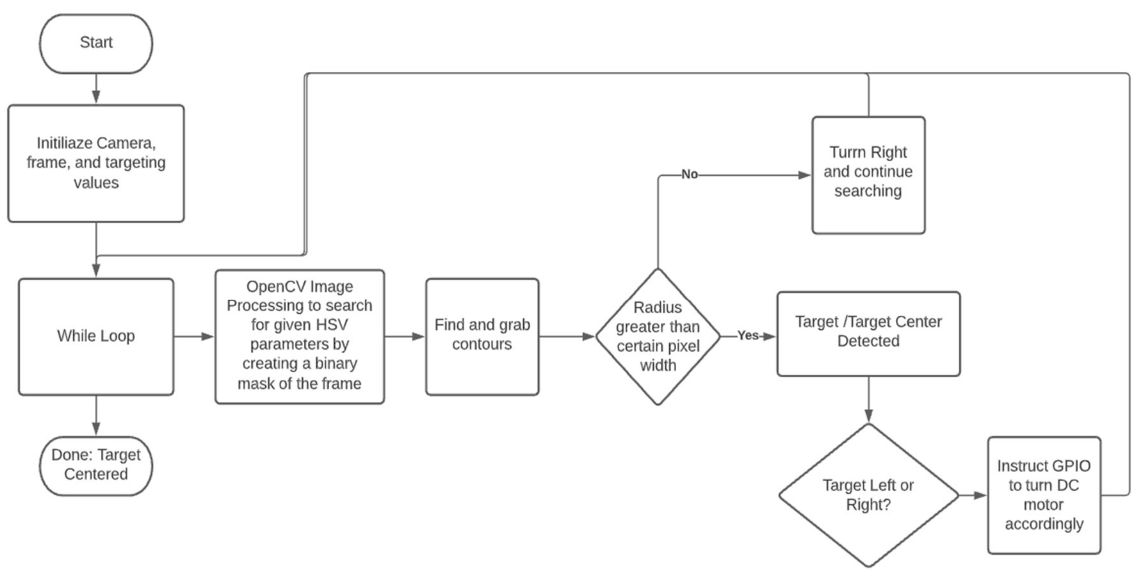


Figure 6: Target Centering Flowchart [2]

3. Design Evaluation

Each aspect of the design is tested throughout the process of implementation. Target detection, distance, height, and hit recognition are tested using laptop webcams and then with the Logitech C270 720p camera. The launch angle, firing, and target centering system electrical components are tested using the DC power supply and multimeter. After confirming the outputs are behaving as expected, tests are done with the Raspberry Pi 4, the system's components, and the Python to control the components.

3.1. Target Detection, Distance, Height, and Hit Recognition Testing

The target detection, distance, height, and hit recognition Python scripts are tested individually and then implemented together. The target detection script behaves as expected, detecting the target and projectile. The target distance and height script utilize the found focal length to accurately determine target distance and height. The target hit recognition accurately determines if the target has been hit by measuring the distance between the centroids and comparing this distance to the target radius.

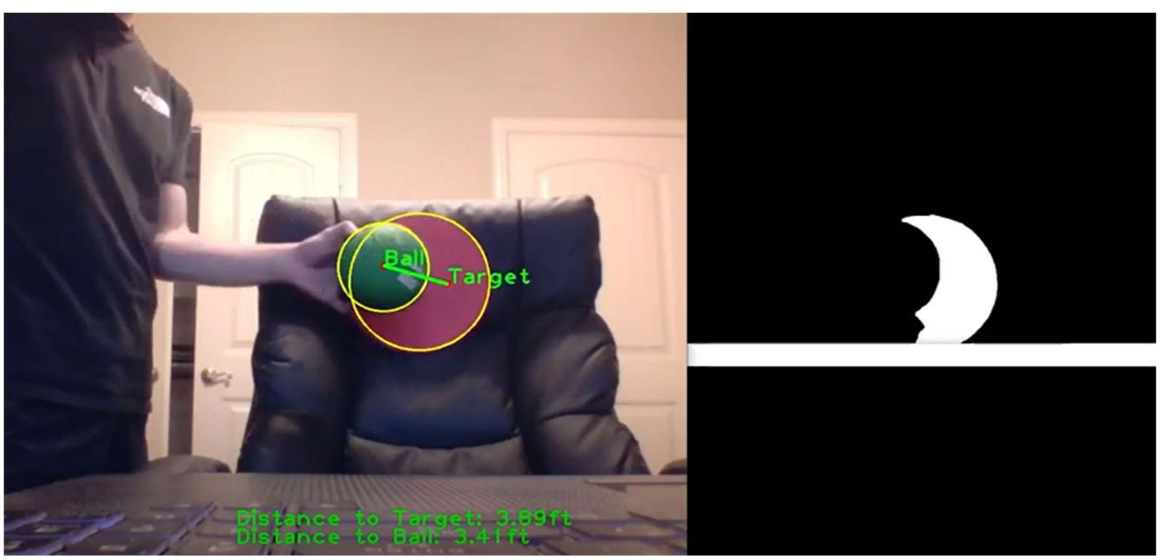


Figure 7: Target Detection, Distance, and Hit Recognition Initial Testing [2]

3.2. Launch Angle and Firing System Testing

Regarding the launch angle system, the 8-inch linear actuator and L298 H-bridge circuit are tested using the DC power supply. The L298 is supplied 12 V and a logic voltage of 5 V. When the enable and input 1 are supplied 3.3 V, and input 2 is grounded, the linear actuator extends. When input 1 and 2 are reversed, the linear actuator retracts. The MPU6050 is tested with test code; the MPU6050 behaves as expected, accurately calculating current angle. All components are then tested together with the Python script for the launch angle system and prove to exhibit proper function. When a desired launch angle is calculated, the linear actuator extends or retracts until the current launch angle meets the desired launch angle.

For the firing system, the 6-inch linear actuator is tested using the same process discussed in the previous section. Since both linear actuators operate at the same voltage, testing is straightforward and proper function is exhibited. The 50 kg S-Beam load cell and HX711 amplifier are tested with test code to determine scaling values using objects of known weight. The load cell operates as intended. The electromagnet circuit is tested with the DC power supply and multimeter. When 3.3 V is applied to the base of the NPN BJT transistor, the coil of the relay energizes, and 12 V is output to the electromagnet. The firing system Python script is tested using all the components and exhibits suitable behavior. The 6-inch linear actuator extends until the electromagnet is pushing against the metal plate on the firing mechanism. The electromagnet is energized, and the firing mechanism is retracted until the desired launch force is met. Once met, the electromagnet de-energizes and releases the firing mechanism. The launch force and angle are correctly calculated using the physics equations discussed previously. When the target is not hit, the launch force and angle are corrected. If the target is hit, the launch force and angle remain the same. When 2 consecutive hits are registered, the program ends.

3.3. Target Centering System Testing

For the target centering system, the DC motor and L298 H-bridge are tested by supplying 12 V to the H-bridge circuit. When the enable and input 1 are supplied 3.3 V, and input 2 is grounded, the motor turns right. When input 1 and 2 are reversed, the motor turns left. After ensuring proper function with the DC power supply, the system is tested with the Raspberry Pi 4 and Python script for target centering. The system functions as intended, moving the catapult left or right until the center of the target is aligned with the center of the camera frame.

4. Design Conclusion

This design automates the launch process of a catapult by using Python and OpenCV to detect the target, determine the target distance and height, and recognize if the target has been hit. The launch angle, firing, and target centering system utilize the Raspberry Pi 4, Python, and various electrical components to achieve the following: center on the target, calculate launch angle and force, adjust the launch angle, launch at the determined force, and relaunch with a different, or same force, based on the prior launches' results. All aspects of design function as intended; however, due to mechanical error in the catapult release point, accuracy of the catapult varies. All in all, this design exhibits the powerful automation capabilities of the Raspberry Pi 4, Python, and OpenCV.

References

[1] Fossbytes - Technology Simplified. (2021, June 10). Raspberry Pi For Beginners (Part – 2): Getting All Required Components. Fossbytes. https://fossbytes.com/getting-started-with-raspberry-pi-get-everything-youll-need-part-2/#1-1-a-raspberry-pi

[2] Holyoak, Jacob. (2021, Oct 16). *Full OpenCV Testing and System Flowchart*

[3] Image Processing in OpenCV. (n.d.). Retrieved from https://docs.opencv.org/4.5.0/d2/d96/tutorial_py_table_of_contents_imgproc.html

[4] L298 Dual Full-Bridge Driver Datasheet. STMicroelectronics, Geneva, Switzerland, 2000. [Online]. Available: Dual full-bridge driver (st.com)

[5] Ramirez, Josiah. (2021, Oct 16) *Electromagnet Circuit*

[6] Rosebrock, A. (2021, July 9). *Find distance from camera to object using Python and OpenCV*. PyImageSearch. https://www.pyimagesearch.com/2015/01/19/find-distance-camera-objectmarker-using-python-opencv/

[7] Rosebrock, A. (2016, April 4). *Measuring distance between objects in an image with OpenCV*. PyImageSearch. https://www.pyimagesearch.com/2016/04/04/measuring-distance-between-objects-in-an-image-with-opencv/

Appendix A

This appendix displays the CAD of the initial design and the constructed prototype. Various aspects have changed from the initial design; however, the prototype functions as intended.

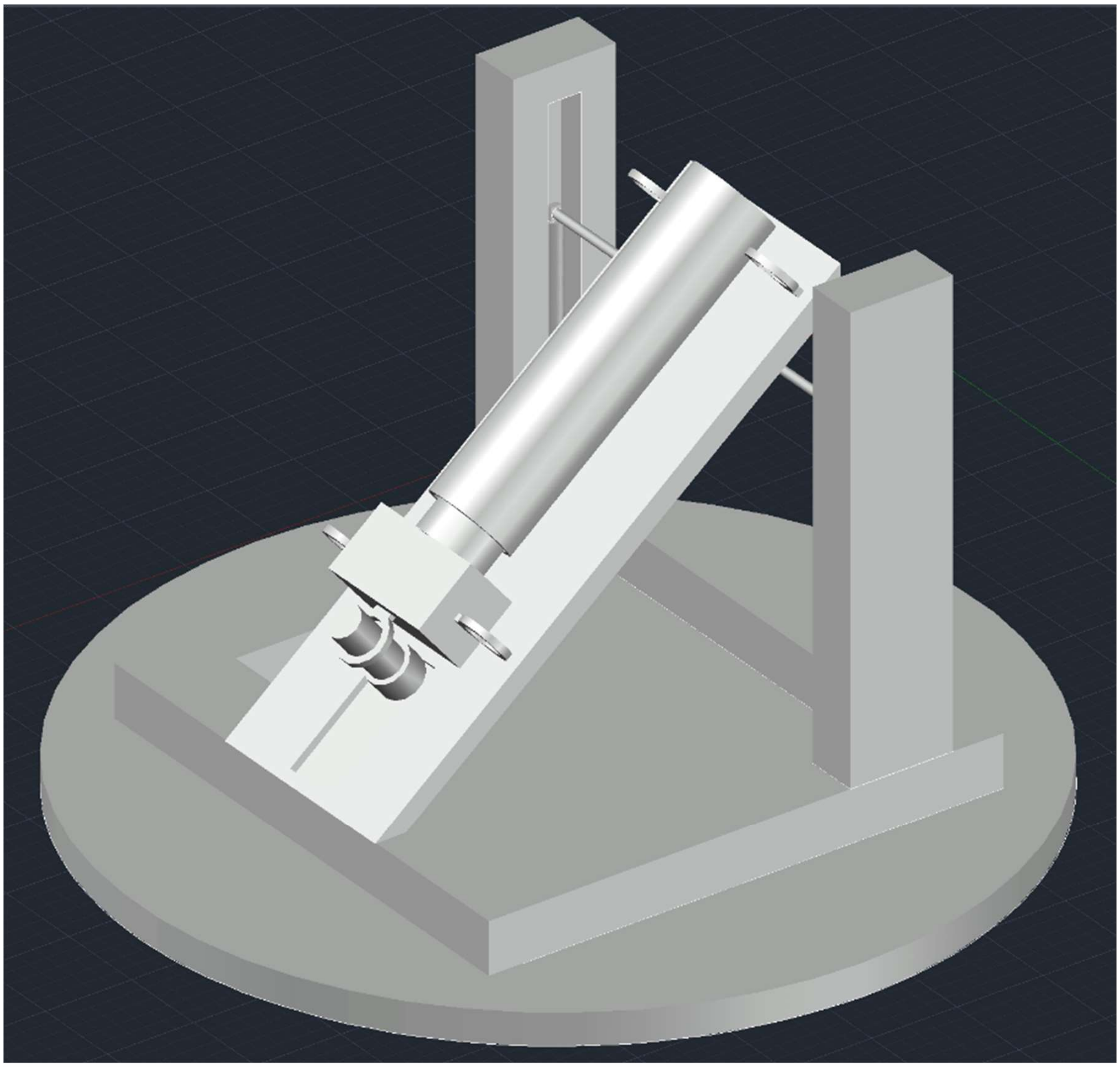


Figure 8: CAD of Initial Design

Figure 9: Final Catapult Design

Appendix B

This appendix contains a state machine diagram describing the function of the automated catapult system.

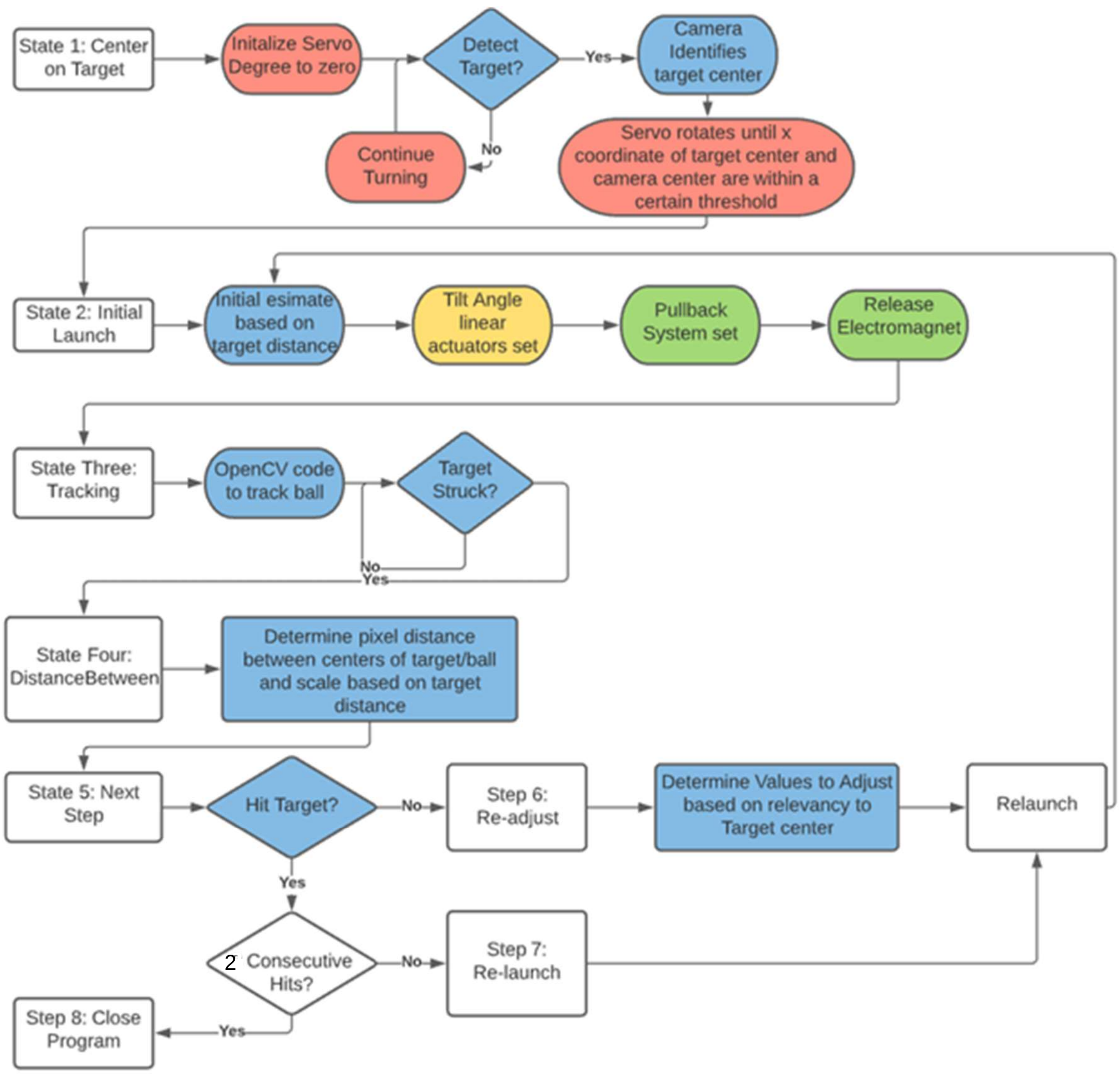


Figure 10: State Machine Diagram for Automated Catapult System [2]

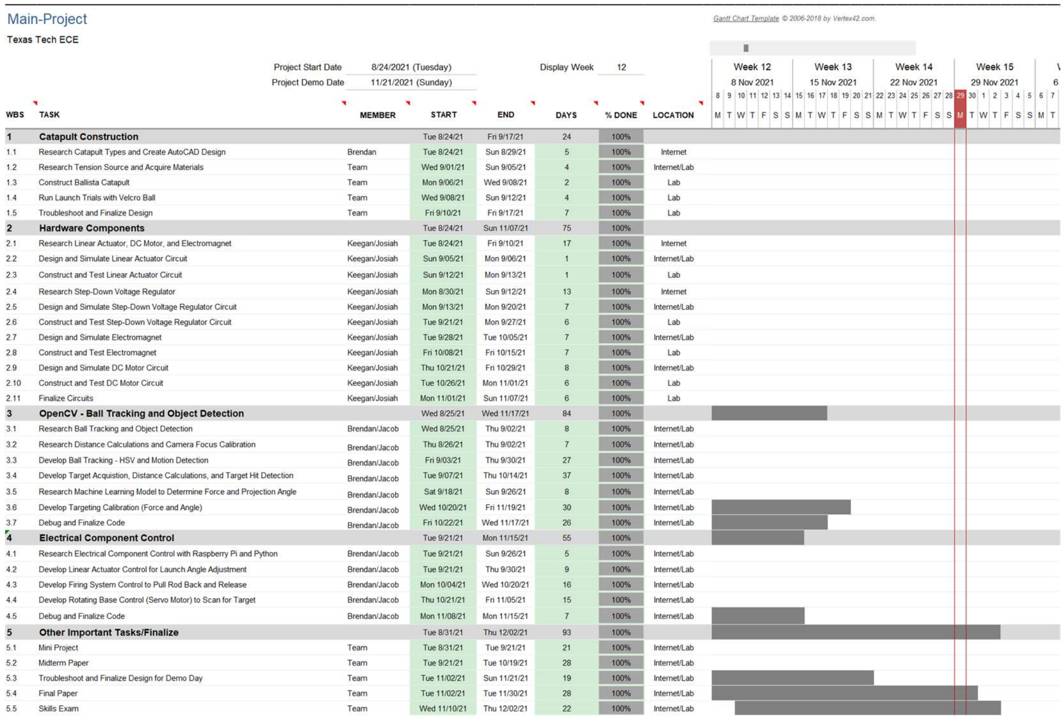
Appendix C

The safety hazards in this design process have been mild and the precautions have been taken to ensure safety. A handsaw and drill are used in assembly; safety glasses are worn and the piece to be cut or secured is securely fastened. Safety glasses are also worn during launch trials of the catapult. The maximum voltage used is 12 V and the maximum current seen is 3 A. The soldering iron approaches temperatures around 700 degrees F; therefore, hardware is carefully soldered with safety glasses on.

Ethical considerations of this design include safety. The projectiles are not harmful but those shooting the catapult should maintain proper distance and follow all safety guidelines when launching. This design is considered an autonomous weapon system; there are multiple ethical considerations surrounding this type of weaponry; however, this weapon is not deadly or fully autonomous so ethical concerns regarding loss of human control and technology designed to kill should be ignored.

Appendix D

The figures below show Gantt chart progress and the current budget spreadsheet. The Gantt chart was followed tightly, progress was recorded each week, and the deadline was met. We ended up under budget and with not as many hours as anticipated.



Main-Project

Texas Tech ECE

Gantt Chart Template © 2006-2018 by Vertex42.com.

Project Start Date 8/24/2021 (Tuesday)

Project Demo Date 11/21/2021 (Sunday)

Display Week 12

Week 12 8 Nov 2021 | Week 13 15 Nov 2021 | Week 14 22 Nov 2021 | Week 15 29 Nov 2021

WBS	TASK	MEMBER	START	END	DAYS	% DONE	LOCATION
1	**Catapult Construction**		Tue 8/24/21	Fri 9/17/21	24	100%	
1.1	Research Catapult Types and Create AutoCAD Design	Brendan	Tue 8/24/21	Sun 8/29/21	5	100%	Internet
1.2	Research Tension Source and Acquire Materials	Team	Wed 9/01/21	Sun 9/05/21	4	100%	Internet/Lab
1.3	Construct Ballista Catapult	Team	Mon 9/06/21	Wed 9/08/21	2	100%	Lab
1.4	Run Launch Trials with Velcro Ball	Team	Wed 9/08/21	Sun 9/12/21	4	100%	Lab
1.5	Troubleshoot and Finalize Design	Team	Fri 9/10/21	Fri 9/17/21	7	100%	Lab
2	**Hardware Components**		Tue 8/24/21	Sun 11/07/21	75	100%	
2.1	Research Linear Actuator, DC Motor, and Electromagnet	Keegan/Josiah	Tue 8/24/21	Fri 9/10/21	17	100%	Internet
2.2	Design and Simulate Linear Actuator Circuit	Keegan/Josiah	Sun 9/05/21	Mon 9/06/21	1	100%	Internet/Lab
2.3	Construct and Test Linear Actuator Circuit	Keegan/Josiah	Sun 9/12/21	Mon 9/13/21	1	100%	Lab
2.4	Research Step-Down Voltage Regulator	Keegan/Josiah	Mon 8/30/21	Sun 9/12/21	13	100%	Internet
2.5	Design and Simulate Step-Down Voltage Regulator Circuit	Keegan/Josiah	Mon 9/13/21	Mon 9/20/21	7	100%	Internet/Lab
2.6	Construct and Test Step-Down Voltage Regulator Circuit	Keegan/Josiah	Tue 9/21/21	Mon 9/27/21	6	100%	Lab
2.7	Design and Simulate Electromagnet	Keegan/Josiah	Tue 9/28/21	Tue 10/05/21	7	100%	Internet/Lab
2.8	Construct and Test Electromagnet	Keegan/Josiah	Fri 10/08/21	Fri 10/15/21	7	100%	Lab
2.9	Design and Simulate DC Motor Circuit	Keegan/Josiah	Thu 10/21/21	Fri 10/29/21	8	100%	Internet/Lab
2.10	Construct and Test DC Motor Circuit	Keegan/Josiah	Tue 10/26/21	Mon 11/01/21	6	100%	Lab
2.11	Finalize Circuits	Keegan/Josiah	Mon 11/01/21	Sun 11/07/21	6	100%	Lab
3	**OpenCV - Ball Tracking and Object Detection**		Wed 8/25/21	Wed 11/17/21	84	100%	
3.1	Research Ball Tracking and Object Detection	Brendan/Jacob	Wed 8/25/21	Thu 9/02/21	8	100%	Internet/Lab
3.2	Research Distance Calculations and Camera Focus Calibration	Brendan/Jacob	Thu 8/26/21	Thu 9/02/21	7	100%	Internet/Lab
3.3	Develop Ball Tracking - HSV and Motion Detection	Brendan/Jacob	Fri 9/03/21	Thu 9/30/21	27	100%	Internet/Lab
3.4	Develop Target Acquistion, Distance Calculations, and Target Hit Detection	Brendan/Jacob	Tue 9/07/21	Thu 10/14/21	37	100%	Internet/Lab
3.5	Research Machine Learning Model to Determine Force and Projection Angle	Brendan/Jacob	Sat 9/18/21	Sun 9/26/21	8	100%	Internet/Lab
3.6	Develop Targeting Calibration (Force and Angle)	Brendan/Jacob	Wed 10/20/21	Fri 11/19/21	30	100%	Internet/Lab
3.7	Debug and Finalize Code	Brendan/Jacob	Fri 10/22/21	Wed 11/17/21	26	100%	Internet/Lab
4	**Electrical Component Control**		Tue 9/21/21	Mon 11/15/21	55	100%	
4.1	Research Electrical Component Control with Raspberry Pi and Python	Brendan/Jacob	Tue 9/21/21	Sun 9/26/21	5	100%	Internet/Lab
4.2	Develop Linear Actuator Control for Launch Angle Adjustment	Brendan/Jacob	Tue 9/21/21	Thu 9/30/21	9	100%	Internet/Lab
4.3	Develop Firing System Control to Pull Rod Back and Release	Brendan/Jacob	Mon 10/04/21	Wed 10/20/21	16	100%	Internet/Lab
4.4	Develop Rotating Base Control (Servo Motor) to Scan for Target	Brendan/Jacob	Thu 10/21/21	Fri 11/05/21	15	100%	Internet/Lab
4.5	Debug and Finalize Code	Brendan/Jacob	Mon 11/08/21	Mon 11/15/21	7	100%	Internet/Lab
5	**Other Important Tasks/Finalize**		Tue 8/31/21	Thu 12/02/21	93	100%	
5.1	Mini Project	Team	Tue 8/31/21	Tue 9/21/21	21	100%	Internet/Lab
5.2	Midterm Paper	Team	Tue 9/21/21	Tue 10/19/21	28	100%	Internet/Lab
5.3	Troubleshoot and Finalize Design for Demo Day	Team	Tue 11/02/21	Sun 11/21/21	19	100%	Internet/Lab
5.4	Final Paper	Team	Tue 11/02/21	Tue 11/30/21	28	100%	Internet/Lab
5.5	Skills Exam	Team	Wed 11/10/21	Thu 12/02/21	22	100%	Internet/Lab

Figure 11: Gantt Chart

Main-Project Budget	**Running Cost**			**Cost Estimate**			**Start Date**	8/24/2021
Direct Labor:	**Rate/Hr**	**Hrs**	**Total**	**Rate/Hr**	**Hrs**	**Total**	**Today**	11/29/2021
Brendan Blacklock	$ 18.00	167	$ 3,006.00	$ 18.00	200	$ 3,600.00		
Josiah Ramirez	$ 18.00	144	$ 2,592.00	$ 18.00	200	$ 3,600.00	**End Date**	11/21/2021
Jacob Holyoak	$ 18.00	161	$ 2,898.00	$ 18.00	200	$ 3,600.00		
Keegan Kelp	$ 18.00	172	$ 3,096.00	$ 18.00	200	$ 3,600.00		
Direct Labor Subtotal			$ 11,592.00			$ 14,400.00		
Labor Overhead (Rate: 100%)			$ 11,592.00			$ 14,400.00		
Direct Labor Total			$ 23,184.00			$ 28,800.00		
Contract Labor:	**Rate/Hr**	**Hrs**	**Total**	**Rate/Hr**	**Hrs**	**Total**		
Lab Tutor	$ 40.00	0	$ -	$ 40.00	2	$ 80.00		
Mark Haustein	$ 200.00	0	$ -	$ 200.00	3	$ 600.00		
Contract Labor Total			$ -			$ 680.00		
Direct Material Costs:			**Total**			**Total**		
(Refer to Material Costs Sheet)								
Direct Material Total			$ 785.36			$ 500.00		
Equipment Rental Costs:	**Value**	**Rental Rate**	**Total**	**Value**	**Rental Rate**	**Total**		
Oscilloscope	$ 1,000.00	0.20%	$ 194.00	$ 1,000.00	0.20%	$ 178.00		
Function Generator	$ 1,600.00	0.20%	$ 310.40	$ 1,600.00	0.20%	$ 284.80		
Power Supply	$ 958.00	0.20%	$ 185.85	$ 958.00	0.20%	$ 170.52		
DMM	$ 1,700.00	0.20%	$ 329.80	$ 1,700.00	0.20%	$ 302.60		
Equipment Rental Total			$ 1,020.05			$ 935.92		
Subtotal Cost:			$ 24,989.41			$ 30,915.92		
Business Overhead (Rate: 55%)			$ 13,744.18			$ 17,003.76		
Total Cost:			$ 38,733.59			$ 47,919.68		

Figure 12: Budget