Automated Safety Spotter

Aaron Larson, Angel Morfa, Chris Weech, Yanlin Ye

Dept. of Electrical and Computer Engineering
University of Central Florida, Orlando, Florida, 32816, United States of America

***Abstract* – Exercise has seen a tremendous increase in popularity over the last 5 to 10 years. As these numbers continue to grow, we see a common pattern of injuries caused by a lack in knowledge on form or by trying to lift more weight than appropriate. This paper describes an add-on tool that aims at increasing the safety of barbell training by using computer vision to track the barbell, two arms powered by linear actuators that pick up the bar from the lifter's hands if help is needed, and a laser-break system that helps detect the lowest point where the arms will initially sit to protect the lifter from a sudden drop of the bar.**

I. Introduction

The Automated Safety Spotter is an add-on tool used to help weightlifters in barbell exercises. With this tool we have tackled the task of replacing a spotter with what is essentially a robot. By replacing a human with a computer, we have increased the safety for solo-gym goers, eliminating the risk of possible human error (distraction, reaction time, lack of judgement, etc.) while spotting. The automation spotter consists of a camera, a display, a computer, and two linear actuators with arms that have an embedded laser-break system. The two liner actuators sit on either side of the lifter behind the barbell's path of travel. After the system has found the users chest height through the calibration, the user can begin there exercise. As the lifter begins the lift the actuators rest at the user's chest and allow him or her to perform the exercise. The camera will be placed directly behind the weightlifter to track the barbell's movement in real time with the utilization of computer vision software. If the bar's motion stops during the lift(indicating a struggle to continue the exercise, the actuators will rise and assist the lifter in completing the lift. We are looking forward to build a highly accurate system to assist weightlifters in the barbell bench press. We hope to promote have lifting, pushing to failure and truly testing the limits in the gym while maintaining or even increasing what was once called safety in the gym. Our system will create the safest way to do that given that a human not reacting on time could lead to injury or even fatality.

II. Overview

A. Goal and motivation

The motivation for this project comes from the recognition of weightlifters' desire to lift increasingly heavier weights and/or go to failure yet are unable to do so because of the potential risks of training without or with an unreliable a spotter. Our goal is to create a solution that will allow the solo gym goer to accomplish his or her goal and attempt the milestones they placed ahead of themselves while maintaining their own safety and the safety of the people around them. Our goals for this project are to create a machine that can increase the safety of gym occupants, specifically those using the barbell bench press without sacrificing the experience of working out. We want to make our project able to fit virtually all bench presses and have the ability to create a unique and customized safety setup for every user that lays on our bench. This safety setup should allow the user to achieve their personal strength milestones no differently that they would with a traditional barbell bench press. This system will also track the path of the bar as it raises and lowers through the users range of motion and able to acknowledge when the user is struggling and assist them in completing that final repetition. The final objective our project will achieve is have an interactive screen that will explain the process of getting your own customized safety setup.

B. Specification

- The calibration sequence determines the low point of user's reps by utilizing a laser-break system located on the inside of the motorized arms to locate the high point of the user's chest. The arms stop lowering within **0.5 seconds** of the laser being broken.
- After the calibration rep, the exercise is initiated with the user pressing a "GO" button on the display which initializes the camera within **5 seconds**, in order to track the barbell.
- The actuator arms assist the user within **2 seconds** if movement of the bar is halted.
- The display has a "DONE" button that disables the system until the next user completes the calibration process.
- The system consists of 2 support arms that sit 38in apart.
- The support arms are powered by 2 linear actuators.
- The linear actuators have an attachment to the rack

- The system has 1 laser-break system.
- The system has 1 display with 800x480 resolution and 14 cm in size. The display allows initiation of calibration sequence and the tracking of the barbell.
- The system has 1 camera.
- The system is controlled via a Raspberry Pi 3B.

III. Construction

A. Arms

Fiberglass is a very simple material to turn from cloth to rigid structure, in its underlying process. Fiberglass cloth comes off the shelf is in what looks to be a blanket or cloth, hence the name. the other two key ingredients in the making of fiberglass is the resin which is a liquid with a consistency of syrup and the other component is a liquid known as the curing agent. The curing agent induces a chemical reaction in the resin to occur and harden, this reaction and hardening gives the final material its strength and rigidity. After the curing agent is mixed into the resin the chemical reaction is underway and there is a limited amount of time until the mixture is unworkable, so it is crucial to work quickly once the process is initiated. To create a full fiberglass structure the resin mixture is applied thoroughly applied to the fiberglass cloth to an extent that it looks like it was dropped in a bucket of the resin. If the cloth is not fully saturated, then the expected strength will be compromised. As the hardening process becomes apparent the substance will begin to turn to a substance that resembles a consistency similar to chunky jelly and as sticky as pine tar. At this point the substance is to difficult to work with and you are better off making another batch of the resin mixture after your current work has dried and adding more layers of cloth if the desired shaped or strength has not been met.

B. Brain Box

The box that our camera is mounted to is going to essentially be the control center of the project. This is where we will house the computer and mount our screen in addition to externally mounting the camera. This box will be made of wood and will be mounted on a stand that will elevate the box 3 to 4 feet off the ground. We have determined that for the open cv software to work optimally, and as we expect it to, this is the ideal height. This height will provide a perpendicular view to the path of the barbell, giving the camera a view of the most physical movement possible.

The reason we are making the box from wood is because it is the easiest and most accessible to work with. Our control center is going to need to be easy to mount to and maintain a low profile. This low profile will provide an aesthetic completeness to our project, but also an increase on the emphasis of reduction in weight. A reduced weight will be crucial in limiting and lowering the center of gravity of the control center. The housing’s stand must be sturdy and have a strong, wide base so if it is bumped, we can be confident in its stability. To ensure a strong base we have a couple of options, we can build a base similar to that of the linear actuator housing, using a couple cross braces and wide feet, or we can utilize a commercially produced tripod for cameras. This will be an ideal case if we have one around that we can use. These tripod’s have the ability to telescope up and down which will allow us to fine tune the height of the camera and find the optimal height for the computer vison software. A tripod will also be simple to mount to given that the are designed to have cameras mounted and removed from them repeatedly in quick, easy, snap and lock fashion.

If we are unable to use a camera tripod we will turn to a fully customized and constructed stand. With this approach we will be allowed to manipulate the material and build construction to optimize the weight distribution to ensure a solid stand for our control center.

C. Actuator Housing and Stand Construction

The construction of the center piece of our project is built of ¾ inch plywood. This structure will act as both the housing and stand for the for the actuators. We have built a base from plywood and 2x4’s for strength and attached a vertical piece of plywood to attach the actuators with additional 2x4’s for strength.

IV. Core Components

A. Raspberry Pi 3B

We decided to pick Raspberry Pi 3B to use for our project because Raspberry Pi 3B has a very powerful CPU and a large memory. It can run a general-purpose OS, such as Linux, and has more powerful standard input and output interfaces. The 1.2 GHz high speed processor is faster than most of the Arduino microcontroller and good enough to make quick response for all the request at a short time. Also, Raspberry Pi 3B has many digital communications on peripherals: 2-UART, 2SPI, and 3-I2C. The number of SPI and UART communication pinout is good enough for our design. Raspberry Pi 3B can be used as a central control server, responsible for communication with the internet, sampling and storing status data reported by Arduino, and processing large amounts of data.

MCU	Raspberry Pi 3B
RAM	1 GB
Maximum Clock Frequency	1.2 GHz
Memory	External SD card
Communication Peripherals	2- I^2C, 2-UART, 3-SPI
Timers	2x8 Bit or 4x16 Bit
Temperature Range (degree)	-40-85
Operating Voltage Range	4.75V-5.25V
Total Pin	40

Table 1 – Raspberry Pi 3B specs

B. Linear Actuator

The linear actuators are the basis of our project and the moving actions our project provides. We felt that two major components of this part that we needed to ensure was speed at a considerably reasonable price. The FUYU FSL-40 was something that checked both of these boxes. By nature, this actuator was able to move around five times faster than some of its competitors in its price range. This actuators ability for high speed was at a cost of weight capacity. This actuator maxes out at a little over 30lbs per arm for vertical weight, but our professors told us this was an acceptable compromise seeing that this is not a mechanical engineering project.

C. Photodiode

The photodiode is a crucial part and arguably the center piece of the laser break system. The selection of the photodiode underwent significant research and planning. We initially knew the need for a photodetector would be crucial but the type we would use was unknown.

After some research we found that the photodiode had the fast response so we dove further to that category given that the speed was crucial given that this was a safety system. We arrived to a desirable solution wit the SFH 2201 photodiode given that it had the largest photosensitive surface area and a speedy response time.

D. Camera

The main use of the camera in our project is to track the barbell and send a signal to the actuator arms to pick it up whenever it stops moving. To do this, we can analyze the video in real time with the help of the many functions available by scanning the video frame by frame in a loop. The Raspberry Pi Camera Module v2 records video at 1080p resolution at 30 frames per second, 720p at 60 frames per second, and 480p at 60 or 90 frames per second, more than ideal for tracking a barbell. It has a Sony IMX219 sensor with 3280 x 2464 resolution and 8 megapixels still resolution. It connects to the controller using a ribbon cable and uses the Camera Serial Interface Type 2 (CSI-2).

E. Display

The main function that we want the display to have is the ability to act as an input for the user to begin the calibration sequence in order to detect the user-specific threshold in which help may or may not be needed when the user is in the midst of a workout. The display we choose for this project is the 5" TFT capacitive touch screen. It supports 5-point touch maximum and the screen resolution can go up to 1920X1080 resolution with the HDMI cable. The display is powered by the MicroUSB cable which is connected to the Raspberry Pi, and the HDMI cable can be directly connect to the HDMI port of the Raspberry Pi. The reason we pick capacitive screen instead of resistive because it has higher touch sensitivity, supports multi-touch, and good visibility.

F. Transimpedance amplifier

To amplify our photodiode's output, we used a transimpedance amplifier or a current to voltage converting amplifier. By grounding both positive and negative inputs of our amplifier we are able to ensure our signal will start at zero and limiting our positive rail to 3.3V we are able to ensure we will not exceed the GPIO pin abilities of the Raspberry Pi.

G. Power Supply

The Automated Safety Spotter is using three power supply, one 24V and two 5V. The 24V power is provided using a common 24V wall supply. The 24V power supply is EAGWELL 24V 15A supply, it is the main power source for the linear actuator and Stepper motor driver. Furthermore, we also have two MEANWELL (RS15-5) 5V 3A power supply, one is to power the raspberry pi and the other is to provide negative voltage to the PCB.

H. Stepper Motor Driver

The FSL-40 linear actuator is built in with Nema 23 stepper motor and stepping motor cannot be directly connected to the DC or AC power supply and must use a special driving power supply (stepping motor driver). The stepper motor driver can control the angular displacement by controlling the number of pulses, so as to achieve the purpose of accurate positioning; at the same time, the speed and acceleration of the motor rotation can be controlled by controlling the pulse frequency, so as to achieve the purpose of speed regulation. The stepper motor driver we use is TB6600, it is a two-phase stepper motor driver, it can realize forward and reverse control. Through the (S1, S2, S3) 3-digit dial switch, you can select 7 Sub-control (1, 2/A, 2/B, 4, 8, 16, 32), and select 8 different current control (0.5A, 1A, 1.5A, 2A, 2.5A, 2.8A, 3.0A, 3.5A) by switching (S4,S5,S6) 3-digit dial switch.

I. Laser

In this project the laser is used to determine the lowest point of the user's chest, the support arms will be activated when the laser is projected on the photodiode. When the laser is parallel to the user's chest, it means that the actuator has reached the lowest point, and the support arms should not go further down for the safety purpose. The Adafruit 1054 is the laser we use for this project. It has the highest wavelength on our selection list and because most photodiodes are the more sensitive to infrared light which is in the 800-900nm range with a pseudo bell curve in sensitivity on either side. The Adafruit 1054 has a wavelength of 650nm, we believe the photodiode will be slightly more sensitive to its light. Which can improve the laser break system response time.

V. Systems

A. Laser Break System

Below you can see a top-level block diagram for the actuators and laser break system. Inside of the actuators you can find both the laser and the photodetector with the power supply feeding into all three. The laser's signal will interact with the photodiode which is attached to either the CPU or an analog to digital converter. The use of an analog converter initially seemed to be an optimizing idea that would allow for some ease in the future for the software but as we found in our research the photodiode is just as fast as the ADC if not maybe faster. In this situation we have elected to remove the ADC in an effort to remove the potential error and complications.

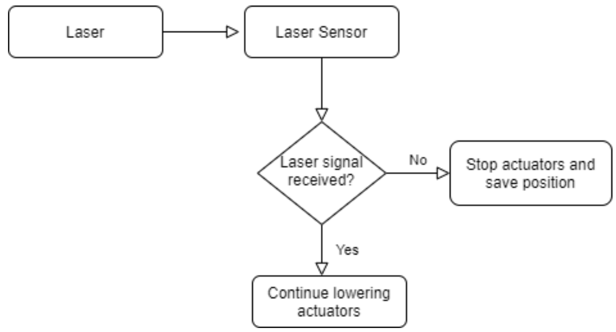

Figure 1 - Laser Break System Flowchart

In this section we give all design plans and testing procedures for both hardware designs and software designs. We also break down the project into all of its subsystems and explain each one; it is this section that you will find flow charts, schematics and complete designs of our project.

B. Computer

The Raspberry Pi is the "brain" of the Automated Safety Spotter, as it is the computer that processes the video feed and all other input and output signals. The actuators, camera, display and laser-break system are connected to it.

When the 'calibrate' button is pressed on the display, and after a 10-second delay to give the lifter enough time to lay down on the bench, the Pi sends a signal to the actuators to move down until the photodiode—located on the inside of the arms—stops detecting the signal from the laser, indicating that the arms are slightly above the lifter's torso, exactly where they should stay (the safest for the lifter) unless help is needed lifting the bar mid-session. The Pi receives the signal from the photodiode (0 volts) and sends another one to the actuators to stop moving, and the software saves the height so that if help is needed, the actuators move up the same distance.

When the 'go' buttons is pressed on the display and after another small delay, the Pi makes the camera start tracking the barbell. As the software analyzes the video feed, it constantly checks whether the bar stops moving. If it does stop, then the computer sends a signal to the actuators, so the arms go up and lift the bar from the lifter's hands. It is important to note that the Pi won't trigger the actuators if at the beginning of the exercise, the user holds the bar still. This will only occur after the bar has already moved at least 1 foot and then stops.

C. Linear Actuator System

The linear actuator system consists of the two linear actuators and the step motor driver. The step motor driver is utilized to create a signal from the voltage given by the power supply. By nature of the stepper motor they need a pulsing signal to 'step' on the rising edge. This is similar to a PWM wave form and it can be utilized to create a step by the motor. Stringing these pulses and steps together drives the step motor, moves the actuators and therefore moves the actuator arms.

VI. Software

A. Open CV

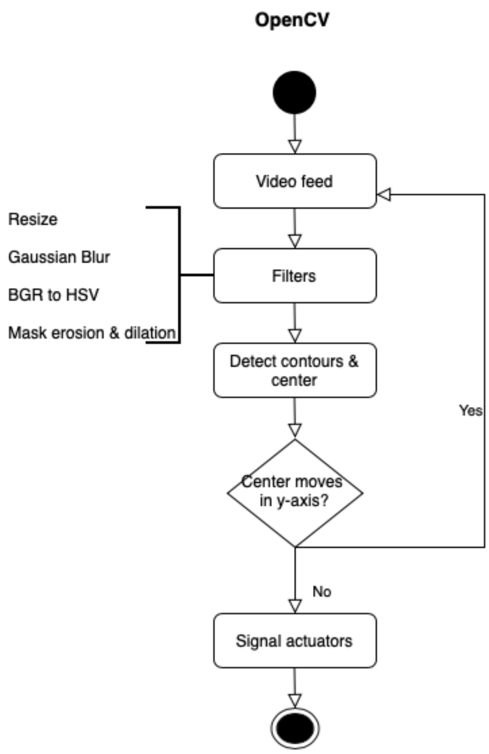

Figure 2 - Open CV flowchart

An essential part of the project consists of the system being able to track the bar and detect if the user needs assistance in lifting the bar. A human spotter would recognize this need for help by watching the user's face showing signs of struggle, his or her arms or legs shaking, and whether the barbell is moving as it is supposed to (that is, the exercise is being performed correctly). But human reaction times are simply not fast enough or reliable enough to maintain the consistency required to maintain high levels of safety while performing dangerous exercises such as the barbell bench press.

We used OpenCV to monitor the barbell via its color. This proved to be very accurate and does not overclocks the Raspberry pi, which occurred with other methods such as background subtraction. After the camera is initialized in software, a *for* loop is used to check each frame and do the following operations to each one of them. The frame blurred and converted to the HSV color model, and a mask is created with a color of the barbell. Then contours are found around the mask, and its center (*x*,*y* coordinates) is calculated. This center is what is being tracked to detect movement. On each new frame, the center coordinates are compared to the coordinates a few frames back (comparing it to the previous frame can cause noise, as a small change in lighting could make two consecutive frames different) and the difference of *y* coordinates is calculated. If this difference is greater than 60 pixels (approximately 15 cm), then it is considered movement. If after approximately 2 seconds the bar has not moved more than that, then the actuators are triggered. This time could be reduced to 1 second or less, but it would interfere with the exercise, as the bench press requires a momentary stop at the top and bottom of the rep when changing directions. If the user were to drop the bar, the actuators sitting at the appropriate height would catch it, preventing injuries.

B. GUI

The main interface was created using Tkinter, the standard Python GUI. This was chosen because it is simple to work with and the interface only requires 3 buttons that execute their specified commands when pressed. Given our display specifications—a small display—it would very easy to clutter the interface, resulting in a negative user experience

C. GPIO

The input signal from the photodiode and the output signals to the actuators are controlled via the general input and output pins on the Raspberry Pi. The actuators require 3 signals: ENABLE, DIRECTION and PULSE. The first one is grounded on the Pi, so that they are enabled at all times. The direction signal is either *low* or *high* if the actuator is moving down or up, respectively. Lastly, the *pulse* signal alternates between *high* and *low* with a small delay in between, and this is what drives the actuators.

The input pin connected to the photodiode receives 3.3 volts when it is receiving light, and 0 volts when it is not. Therefore, when the user is performing the calibration sequence, the actuators will move down until 0 volts (or LOW signal) is received on the pin, indicating that the arms are 'chest-high.'

VII. Design and PCB

A. Design

Below is a block diagram that displays our full design with signals traces color coded to show how the signal, power, and ground lines move about the system.

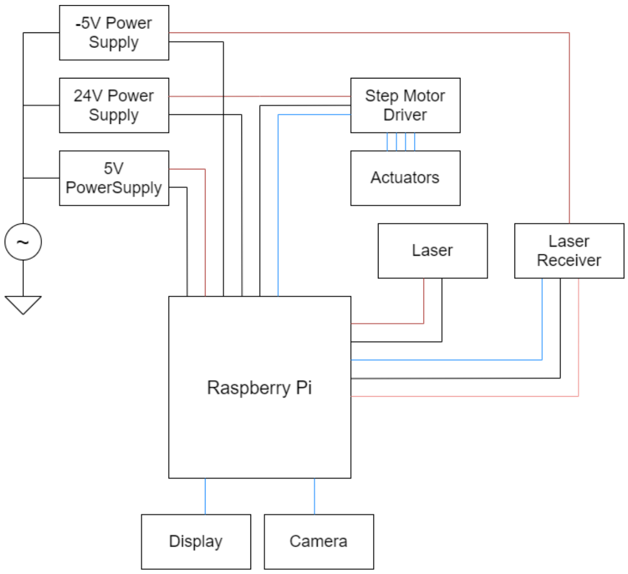

Figure 3 - Full design block diagram

B. PCB

Below is a display of our PCB layout. We had the pins connecting back to the Raspberry Pi. 1 - Ground; 2 – 3.3V; 3 – output of the amplifier; 4 - -5V; 5 – Ground.

We lowered the positive rail to 3.3V to ensure our signal will not rise above 3.3V(this is the threshold for the Raspberry Pi's GPIO pins). Also, by grounding both positive and negative input pins of the op amp we ensure that with no light we will have an output of zero because with no light there is no current. When light has illuminated the photodiode, this allows the current to flow therefore amplifying up to our positive voltage rail and the Raspberry Pi will read this as high. We used a 76.8K gain resistor yet because we were unsure of the signal attenuation the laser would have through air, we prepared two larger resistors at almost double and triple the size. In some preliminary test we found that the laser was plenty strong enough to provide ample photos to the p-n junction of the diode and give us the current needed to create the change in voltage we needed.

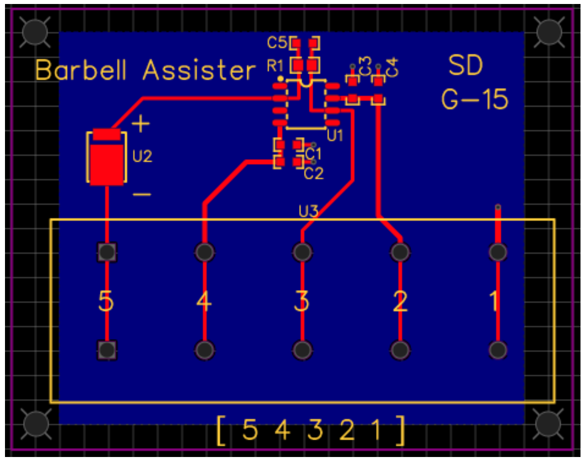

Figure 4 - PCB layout

VIII. TESTING

We tested each component to make sure it works properly due to its importance to the project. The first thing we needed to test was the power supply, ensuring we were getting the power we desired utilizing the multimeter we check the range of adjustment which was in the neighborhood of +/- 0.7V. The computer and display were tested in tandem seeing if the communication software and firmware between them was correct. The way we tested these two components is to first complete the configuration tutorial provided in the user manual of the display, which will allow us to complete the connection of the Raspberry Pi 3 Model B and will then allow us to further customize the capabilities of the display after configuring it. Next we test the capability of the display's input, by creating a simple code in which by touching the display screen there will be some sort of notification by way of the computer, such as an LED flashing or something of that nature. After multiple simple testing scenarios, we will continue to more complex testing situations such as providing signals from the Raspberry Pi 3 Model B to create movements in the linear actuator, after the linear actuator is connected to the stepper motor driver and Raspberry Pi properly.

Testing of the PCB was extremely strenuous and really forced us to think back to our prerequisite coursework. Initially we hooked up plus and minus 5V to the rails. This cause our signal to jump from a ballpark of 1V to -3V. This was unacceptable given that the pi could not accept negative voltage of the GPIO pins. To mitigate this issue, we pushed the negative rail to zero and didn't see any more negative voltages. This turned out to be a major issue given that this particular op amp needed to see a negative voltage on the negative rail so the ground on this pin created a lot of inconsistencies in the board's performance. Coupling this with an error that was overlooked when designing the PCB, we were in a way destined for failure. We eventually grounded both input pins flipped the photodiode and gave -5V to the negative rail which gave us a low reading when there was no light. Making the positive rail 3.3V to ensure the voltage doesn't rise above the threshold of the GPIO pins of the pi we had a successful transimpedance amplifier.

When it came to testing the laser break system we found it to very inaccurate and inconsistent at the input to the pi, yet at the output of the amplifier it was very clear what the voltage was. We began to test with an oscilloscope at the pin and found that because of the pulse functions for the actuators and those wires being ran next to our output our assumed fear was confirmed, there was an extreme amount of noise at this point. We added a 10uF and 22pF decoupling capacitors to the GPIO pin and with this modification our Vpp went from over 1.5V to less than 0.2V.

Software testing in our project was a lot of testing the camera in conjunction with the open cv code. Also, that when the 'calibrate' button is pressed on the display and after the timer finishes, the actuator arms start moving. When the 'go' button is pressed, the camera should start tracking the bar.

One instance of an issue that was never considered was the time before beginning the exercise. In this time the user may wait and prepare for the lift before exercising. In this period of waiting the camera would see the lack of movement and raise the arms before the user has even began the exercise. This prompted the decision to allow the camera to track the bar only when it begins its initial movement, completely eliminating the possibility of the arms ascending due to the lack of movement of the bar that occurs when the user is yet to begin his/her workout.

IX. Conclusion

In conclusion the project was able to meet all of the initial specifications that we had set for it. This project allowed us to not only put into practice our knowledge of microelectronic technology but also our knowledge in coding processes as well; forcing us to identify creative ways to utilize the equipment at our disposal and make them function in a way that is beneficial to the overall success for our project.

This project was a tremendous learning experience not only to nail down our education from prerequisite coursework but in allowing and forcing us to exercise skills in research, planning, and problem solving. We have learned how a larger scale project is transformed from an idea to a completed design and what we can expect the workflow to look like when entering the workforce. We learned about the skills that are pertinent for our success in transferring from academia to the workforce; whether it be a STEM field, or a management position, the soft skill gained will be invaluable. The skills and knowledge gained through senior design were not unknown due to a lack of teaching in the classroom but unknown due to an inability to be taught in a classroom. I personally can say I have seen a change in myself over the last 8 months as to how I look at and approach problems on a daily basis and I feel that this process of senior design has been a massive assistance in my growth as an engineering and a future employee.

The Team

Angel Morfa is a senior at the University of Central Florida and will be receiving his Bachelor of Science in Computer Engineering in August 2020. His professional interests include back-end development, machine learning and computer vision.

Yanlin Ye is a graduating Electrical Engineering major at the University of Central Florida. He will be receiving his Bachelor of science in Electrical Engineering in August of 2020.

Aaron Larson is an Electrical Engineering student at the University of Central Florida and plans to begin work as an Electrical Engineer after graduation in the field of Microelectronics.

Christopher Weech is an Electrical Engineering major at the University of Central Florida who plans on beginning his engineering career after graduation focusing on the field of power systems.