Light Guide Solar Concentrator

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***Abstract*— This paper presents a novel photovoltaic solar concentrator, the required supporting mechanical and electrical systems, and a companion mobile app. The solar concentrator has a planar shape. This is an improvement over concentrators that require a collector or additional reflector positioned above the initial reflector. The presented device requires less space and is more attractive in appearance. Additionally, methods to reduce optical losses in such a device and in potential future improvements are presented.**

***Keywords*— Solar, concentrator, energy, microcontrollers, maximum power point tracking, senior design project, mobile application.**

I. INTRODUCTION

Concentrated photovoltaic (CPV) devices have the potential to be a major player in the renewable energy market. These devices allow a smaller number of solar cells to be used, because the light is concentrated into a small area. Using fewer solar cells means that more expensive, higher efficiency solar cells can be used. However, a major disadvantage of these devices is that they are bulky and hard to manufacture. In this work, we present a more compact solution that still offers a concentration factor of 6. This solution is also scalable and, once manufacturing methods become mature, the cost to manufacture this device will be lower than traditional solutions.

In addition to the concentrator, we present an android app to control the system. The android app is innovative in that it allows the user to understand the status of their system easily and in detail. The app attempts to bridge the gap between technical data and non-technical users by displaying power generation over time, current status, and empowering the user to control their system manually. The mobile app will also allow the user to monitor the status of their system anywhere they can connect to the internet. This app also calculates the amount of money the user has saved by using the system and how long it will be until the user has made enough money to pay for the system.

The concentrator will only function properly when it is directly facing the sun. Therefore, a dual axis tracking system is required. This tracking system and various other electronics will be controlled by an embedded processor. The embedded processor will send status data to a server where it will be stored. The android app will access the data on the server whenever necessary and can be updated in sudo-realtime. Using this architecture, data about the status of the system can be available at a moment's notice. The embedded processor will also ensure that the maximum power point is achieved through the use of a MPPT circuit and algorithm. By measuring the voltage and current at the solar cell and the battery we can ensure that the voltage at the battery is sufficient, yet low enough to maximize the current flowing through and therefore reducing the charge time of the battery. To maximize the battery longevity, a current cap is placed to not overload the battery.

This entire system functions as one complete unit, maximizing the energy captured from the sun and utilizing it in some of the most efficient ways possible to ensure that the user is getting the most out of their renewable energy source.

The motivation for any photovoltaic solar concentrator is to reduce the surface area of solar cells required to capture a given amount of solar energy. When the surface area is reduced, more expensive solar cells, such as multijunction solar cells, can be used while staying within a given budget. These more expensive solar cells have higher efficiency percentages of up to 46% which represents a significant improvement over the 20% efficiencies of silicon solar cells.

The advantage of a LGC over traditional solar concentrators is that the former is more compact and easier to install. Traditional solar concentrators use large parabolic mirrors to focus the light to a point that is above the mirror where the solar cells are positioned. On the other hand, LGCs require no large curved surfaces to concentrate light and the solar cells are not positioned above the mirror. Instead, the LGC redirects light to either side (see Figure 1.) This removes the need to create an additional mounting system for the solar cells. When considering the scale of a solar farm, this simplicity offers a substantial reduction in cost.

II. PROJECT REQUIREMENTS

The primary goal of our design is to concentrate energy with the concentrator into a solar cell, store this energy in a rechargeable battery, and make information about the status of the system available for the user. A secondary goal is to create a design that is more compact than existing solar concentrators. Our design is unlike most other designs in that it is a planar shape rather than a traditional parabolic shape.

Additional requirement specifications were made with set values to ensure we were iterating with a goal in mind. Some key specifications for the project include:

- The solar concentrator has a concentration value above C = 2.
- The solar concentrator is less than 5 cm thick.
- The concentrator has a mass of less than 1 kg.
- The system tracks from east to west automatically from -60 degrees to 60 degrees and north to south from 0 to 55 degrees.
- The minimum power output is greater than 0.5 Watts.

Ultimately, this design is a scale model of a larger concentrator design, mainly due to budget constraints caused by the high cost of optical components required to bend the sunlight. Therefore, ensuring our electrical components were powered by the system was not a design specification. <insert proof why it wont work>. However in a larger system design, the power generation scales with the size, as expected, but the power cost of electrical components only slightly increase. The most costly increase would likely be the tracking system, as we were able to use servos that could handle the load of the glass; on a larger scale, these would need to be improved to handle the higher load.

III. SYSTEM COMPONENTS

This design consists of four primary components: solar concentrator, solar tracking system, electrical power control system, and a mobile application that utilizes an online data. These all work in tandem to ensure that the maximum power is being stored and presented to the user at near real time intervals. This section details how these components work together, and the next sequential section will discuss design choices for those components.

A. Solar Concentrator

As shown in Figure 1, the device consists of a thick polycarbonate layer, a gradient index layer, at a layer of 30 - 60 - 90 prisms that are coated with silver that acts as a mirror. Once the light has been reflected, the gradient index layer will bend the light towards the side of the polycarbonate layer. The indexes of refraction have been chosen such that the light will not be able to escape causing total internal reflection. This differs from a complete traditional waveguide, because it will not trap light that travels too far in the polycarbonate layer. Therefore, the dimensions of that layer must be chosen so that light from the farthest prism does not escape back into the gradient index layer.

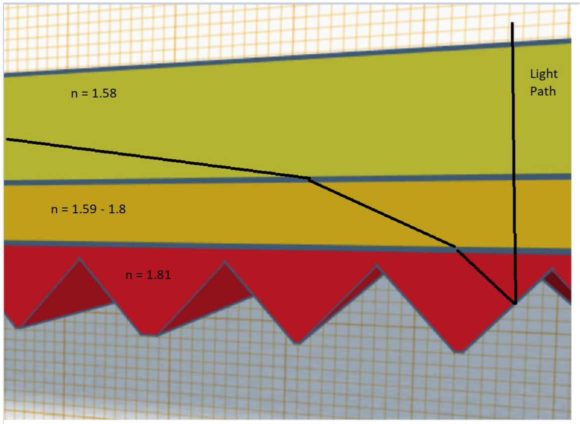

Figure 1: Light Guide Concentrator with Light Path

The biggest component of the optical losses that should be expected are due to Fresnel reflection. A secondary source of loss happens at the mirror surface. In order to prove that the losses due to

Fresnel reflection can be reduced to an acceptable level, a matlab script was written. The results are shown in Figure 2. To approximate a gradient index layer, the script calculates the losses as if the gradient index layer is a stack of materials with an increasing number of layers. As the number of layers increases, the losses decrease and tend toward zero.

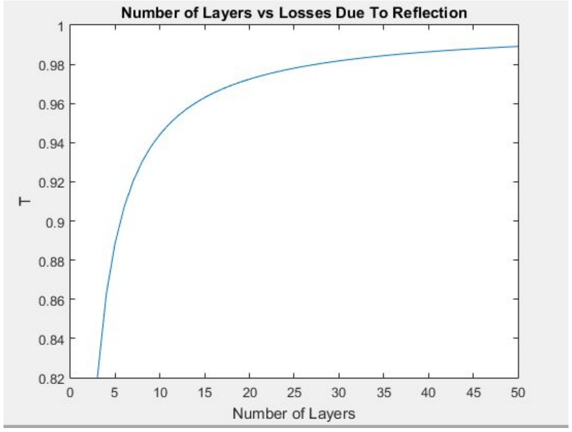

Figure 2: Projected Losses Due To Fresnel Reflection

Another major limitation of the optical system in this project is the cost of the components. For this reason, only a small prototype was constructed. The concentration factor had to be cut in half as well, because there was not enough funding for the prism components.

B. Solar Tracking System

The position of the sun is tracked with a quadrant photodiode and a pinhole as shown in Figure 3.

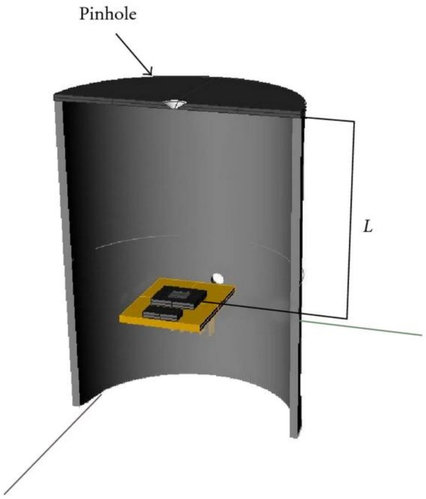

Figure 3: Pinhole and Quadrant Photodiode Position Sensor

The light enters a pinhole and depending on the angle of incidence it hits a different quadrant of the photodiode. Using the output of the QPD, the microcontroller calculates the new adjusted angle that the concentrator should move to, and creates a PWM signal that is sent to the servos in order to maintain this angle. The new adjusted angle is calculated by the microcontroller by moving the concentrator towards the sensor with the highest intensity using a threshold of change to ensure that the solar concentrator system isn't wasting power or computing time on miniscule changes in the sunlight readings from the corner sensors. The problem with this setup is that the angle of acceptance is limited if the distance between the pinhole and QPD, L, is large. If L is reduced, the precision of the device is reduced as well. In order to overcome this problem, a scanning modes was implemented that finds the position of the sun. Once the sensors are activated, they are used to tweak the tilt and rotation of the device so it is directly facing the sun.

C. Electrical Power Control System and MCU

In order to operate the photovoltaic cells at peak efficiency, we need to ensure that the cells are producing their maximum power point. This is determined through the use of a maximum power point tracking algorithm and an additional DC-DC converter. This circuit controls the voltage at which the photovoltaic cells operate, ensuring that the photovoltaic cells are operating at peak efficiency through the tradeoff of current and voltage. Maximum power produced by photovoltaic cells can vary with solar radiation, ambient temperature, and solar cell temperature.

In addition to the circuit design, an appropriate battery capacity must be considered based on the output current of the solar cells. Due to the scale model nature of this project, a Lithium-ion battery makes the most sense with capacity ranges in the hundreds of milliampere hours.

The microprocessor will control data communication between the integrated circuits needed for maximum power point tracking as well as communication between the sensors and servos. Ultimately these readings will be pushed to the end-user in a digestible fashion.

D. Mobile Application and Database

The design's target audience is the everyday house user who owns a smartphone and is interested in seeing the benefits of their solar device immediately. An additional mobile application to the solar hardware will grant the user instant access to the data and statistics that the design is producing. The user will be able to read and understand basic statistics such as:

- Solar power generation
- Cell efficiency
- Cell temperature
- Power going into the cell
- Power going out of the cell
- Tilt angle of the device
- Rotation angle of the device

In addition to displaying the current status of the device, the mobile application also features power generation over multiple time periods. The user will be able to see how much power was generated over a daily, weekly, and monthly basis.

The database that the mobile application will retrieve data from will be updated in real-time, allowing the most recent data entry to be visible as soon as it is added.

IV. DESIGN

Throughout implementation and testing of our design, we had many iterations and revisions of each component of the system. This section details those components and final design choices, and how these decisions impacted the design.

A. Solar Concentrator

The process of designing the solar concentrator consisted of choosing materials with appropriate refractive indexes, choosing dimensions of each layer, and choosing index matching fluids to prevent air gaps. First, the most difficult to find component, the gradient index glass, was obtained via donation from Lightpath Technologies. Then, the other parameters of the device were chosen to fit with that material. The glass obtained had a index ranging from 1.59 to 1.8. Polycarbonate was chosen as the top layer, because of the index of refraction, light weight and low cost compared to glass. The prisms were chosen because of the index of refraction and availability of the correct shape. These indexes were also chosen because of the resulting light path and resulting concentration factor. Given the prism index of 1.804, the angle that the light makes with the normal in the polycarbonate (n = 1.585) can be found using snell's law as shown in equation 1.

$$Theta_f = sin^{-1}(1.804 * sin(60)/1.585) = 80.29 \quad (1)$$

The concentration factor is the ratio of the area of the aperture to the area of the absorber. In the case of this concentrator, the area of the aperture is the area of the plexiglass layer and the area of the absorber is the area of two of the sides of the plexiglass layer. The thickness of the plexiglass layer is determined by Theta_f and the length of the concentrator, because layer must be thick enough for light reflected on either end to pass to the other end without passing back into the gradient index material. For example, if the concentrator is 22 cm long and Theta_f is 80.29, the plexiglass layer thickness can be calculated as shown in equation 2.

$$t = 11/tan(80.29) * (1 / 2) = 0.94\ cm \quad (2)$$

If the width of the concentrator is 2 cm, the aperture area is 22 cm^2 and the absorber area is 7.52 cm^2. The concentration factor can be found as shown in equation 3.

$$C = A_a/A_{abs} = 2.94 \tag{3}$$

The potential concentration factor of a device with these refractive indexes is 5.86, but due to funding restrictions a smaller device was constructed.

The optical losses in the design will mostly come from absorbance in the silver mirrors and losses due to Fresnel reflection because of small differences in the refractive indexes. It is important to note that the closer the refraction angle gets to the critical angle, the greater the loses to Fresnel reflection becomes. Therefore, it is more important for the differences between the indexes of adjacent layers to be lower closer to the top of the stack.

B. Solar Tracking System

As discussed in the system components section, the position of the sun is tracked with a quadrant photodiode. The quadrants were converted into X and Y positions using equation 4.

$$X = \frac{(x+)-(x-)}{Q1+Q2+Q3+Q4} = \frac{(Q1+Q4)-(Q2+Q3)}{Q1+Q2+Q3+Q4} = \frac{X_{Diff}}{SUM}$$

$$Y = \frac{(y+)-(y-)}{Q1+Q2+Q3+Q4} = \frac{(Q1+Q2)-(Q3+Q4)}{Q1+Q2+Q3+Q4} = \frac{Y_{Diff}}{SUM} \tag{4}$$

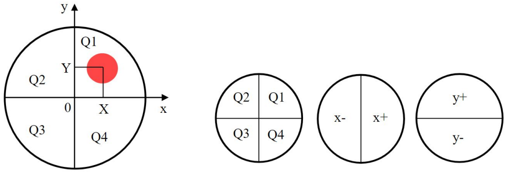

Figure 4: Quadrants Assignment of QPD

The quadrant assignments of the QPD are shown in Figure 4. When the X and Y coordinates are obtained, the tilt and rotation servos are slightly adjusted in order to center the image of the sun within the QPD.

Due to the customized nature of our project, 3D printing an enclosure to house the components seemed like the most appropriate option. Figure 5 depicts the final model. The additional attachments that are disconnected from the main housing unit in the print were made for attaching the quad-photodiode as close to the central point of the active area of the concentrator in order to ensure proper tracking accuracy, and the non concentrated solar cell and photodiode for comparison measurements.

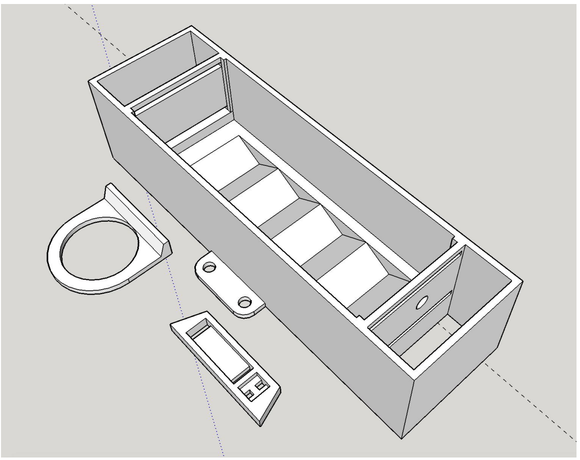

Figure 5: 3D printed housing unit

C. Sensors

In order to understand the status of the system, photodiodes, temperature sensors and solar cells were used. One photodiodes and one solar cell were exposed to concentrated and unconcentrated light. The output of these components was compared to monitor the concentration factor of the device and prove that a solar cell exposed the concentrated light does produce more energy. Temperature sensors were used to monitor the status of the solar cells to insure that they do not overheat.

D. Electrical Power Control System

The PCB for this system realizes a DC/DC convertor in the form of a PWM controlled H-bridge buck/boost topology to ensure that the maximum power point is being followed while transferring power from the solar cells to the battery. Multiple integrated circuits are utilized to ensure that the four transistor gates within the H-bridge are operating appropriately as high-side buck, low-side buck, high-side boost, and low-side boost. The SM72442 and SM72295 were used for MPPT control and H-bridge driving, respectively. By following the datasheets, we were able to choose configuration resistors and components for current sensing and limiting as well as transistors that match the specifications of the chip. A simple inductor intersects each transistor and charges and discharges according to the control signals.

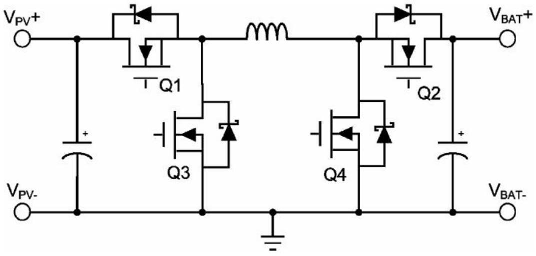

Figure X: Buck-boost topology

In addition to this example interface, power for the integrated circuits and configuration resistors are found on the board in order to realize a full MPPT PCB. I2C is utilized for communication of the power output and voltage and current readings from the integrated circuit elements like the maximum power point tracking chip and the full H-bridge driver chip in order for the microprocessor to see these results and pass them along to the end-user.

The microprocessor was required in order to handle the communication between our power system results and the wifi module in order to finally send the relevant readings to the end user in the mobile application. The MCU chosen was the ATMega2560 due to its large number of analog pins and vast support for elements in our design like serial communication, I2C, and servo control. The MCU handles polling sensors from both the power control circuit and optical elements in order to gather information needed to send to the database. This occurs periodically every minute in order for the end-user to see the resulting behavior of their device throughout the day.

The ESP8266 (ESP-12E) provides connectivity between the microprocessor and the database solution. Every minute, the relevant sensor readings found in Figure X are pushed to the database in addition to the current timestamp. These readings provide all of the information required for power calculations to be done on the front-end. By pushing the raw values to the front-end, flexibility and scalability is given for new application solutions, rather than calculating power efficiency on the microprocessor and having to modify the embedded code after the device is already complete.

E. Database

Firebase is a real-time database solution used in order to push reading results from the MCU and pull results to the front-end mobile application. Firebase allows scalability of data and applications connected by the use of Google's Cloud Platform and intelligent NoSQL storage techniques in order to push and pull data at lightning speeds. All data is stored in a hash table-like structure, which results in suboptimal query options with the tradeoff of reduced latency between requests and results.

Firebase stores data in a tree-like structure which paved the way for a simple parent node that contained all of the entries sent from the ESP WiFi module. Since these entries are pushed in chronological order, pulling data from the database to the end-user proved simple especially when creating graphs to represent efficiency over time.

F. Front-end Mobile Application

To build the mobile application the team agreed on using React Native, which is an application framework that allows software engineers to build mobile apps using only JavaScript. It uses the same fundamental UI building blocks as regular Android applications. The mobile application is going to be the information hub for the user to understand how their solar device is operating.

Programming the mobile application solely using the JavaScript language gives the software designer the ability to use the same code on iOS and Android devices, saving development time and cost. React Native uses the Fetch API for networking properties. It will request data and information over the network and retrieves a response to the request. The requests may come when the user selects one of the options, periodically throughout the day, or indefinitely. The development platform also provides a live-reload feature that allows the software designer to see the changes made to the application immediately.

V. TESTING

Testing the losses of the solar concentrator due to fresnel reflection were performed with a 532 nm laser diode. Input power and output power were tested with normal incidence and with a 60 degree incident angle. During the process of testing, it was determined that the biggest source of loss was the layer of index matching fluid between the polycarbonate and gradient index layers. This makes sense, because at this point the angle of incidence is approaching the critical angle. In order to mitigate these losses, multiple layers of fluid with indexes of refraction that varied by 0.01 were applied at the interface. Figures 6 and 7 show that as the number of fluid layers was increased from 2 to 5 the transmission coefficient increased.

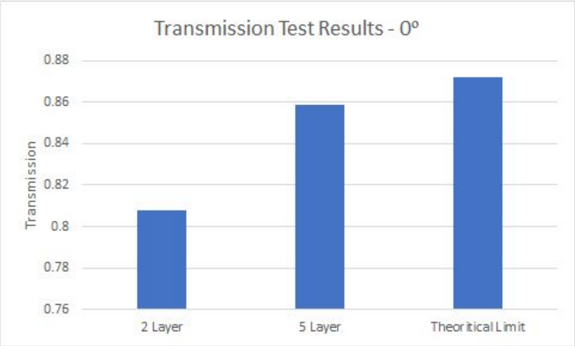

Figure 6: Normal Incidence Test Results

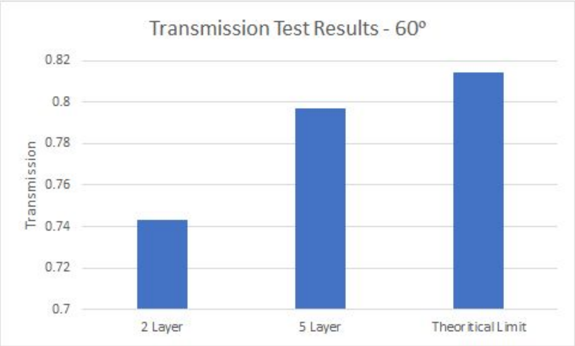

Figure 7: Sixty Degree Angle Incidence Test Results

In order to ensure a proper realization of the MPPT and MCU circuit, the circuit elements were initially breadboarded. From this we were able to test what the real world buck/boost response would be from the solar cells to the battery. In addition, the sensor responses from both the photodiodes and servos were tested to ensure proper calibration and movement angles. The expected behavior of the solar cells are depicted in Table 1.

Table 1: Hardware Testing

	Solar Cell	Solar Cell Array	MPPT Out
Expected	3.4V, 3.8mA	6V, 11.4mA	4.2V, 22mA
Real	0.4Voc, 4mA	5Voc, 8mA	4.2V, 15mA

After realizing the PCB, the individual embedded components are tested to ensure proper solder connections were made. By flashing the ATMega2560 with code from the breakout board, the remainder of the components can be tested for functionality.

VI. FUTURE IMPROVEMENTS

Future improvements that can be made to this system include creating a single piece optical element, reducing the height of the prism layer, increasing the concentration factor by getting closer to the critical angle and including an antireflection coating on the top layer. A single piece could that accomplishes the purpose of all three layers can be achieved by using a mold and a material that with a tunable refractive index. The gradient index material used in this project is created by melding glasses with different indexes and combining them in a crucible. The denser glasses which also have higher refractive indexes settle to the bottom of the mixture. A mold in the desired shape could create a single piece that accomplishes the design of this device. This improvement was not made in this project due to funding limitations. Another option is to find a plastic material with a tunable refractive index that can be molded at much lower temperatures. A single optical element device also makes approaching the critical angle much more feasible. Getting closer to the critical angle increases the concentration factor and reduces the required thickness of the top layer. An antireflection coating was not implemented in this project, because there was no access to equipment to apply one, but it would improve the device a small amount.

Some improvements to the mobile application are the ability to cross-platform the app on iOS devices, fully utilizing the capability of the React Native development platform, being able to send tilt and rotation angles to the microcontroller to manually rotate the solar cells, and displaying weather statistics to inform the user of how the weather patterns could affect the solar power generation of the solar device.

VII. CONCLUSION

This project is comprehensive in solar energy efficient technologies to provide the user with the best experience possible in their hand and on their wallet. From energy capture to energy storage, this project encompasses a number of techniques to ensure that the maximum amount of power is transferred from point a to point b. By reducing the size and quantity of necessary solar cells, funds could be focused on fewer, more expensive, more efficient cells in order to maximize the solar energy captured within the CPV optics. This solar energy, once trapped within the final gradient index layer closest to the top, is concentrated to C=2.5, motivating the need for a higher end cell. A maximum power point tracking switching circuit and algorithm are implemented to ensure that sufficient voltage is maintained when energy moves throughout the system from the cell to the battery, all the while maximizing the current (within a particular threshold limit) to speed up the charging process.

Acknowledgements

We'd like to thank Lightpath Technologies for providing gradient index glass, Dr. Sayan Chandra for assisting us with the silver mirror coating and Sligo Inc for allowing us access to a water jet cutter.

Biography

Kyle Merritt

Kyle Merritt is a undergraduate student at UCF. His major is Optics and Photonics Science and Engineering. He also works as a software engineer at Ocean Optics where he builds software that helps customers use their spectrometers more effectively. His main focus for this project was fully designing and implementing the optical components required to concentrate sunlight, as well as embedded code on the MCU for sensors of optical components.

Justin Kolnick

Justin Kolnick is an undergraduate Computer Engineer at the University of Central Florida. He currently works at the Student Union implementing technical solutions for students and clients alike. His main focus for this project was the electrical design as well as the embedded code needed for communication between the MCU and the database. In addition, he also fully designed and printed the 3D model required to house the device components. Moving forward, he would like to work in computer vision and machine learning fields as a software engineer.

Matthew Armogan

Matthew Armogan is an undergraduate Computer Engineer at the University of Central Florida. He is currently in the College-Work Experience Program at Lockheed Martin as a Reliability Engineer Contractor, specializing in failure data analysis and database and software design. His main focus for this project was the software design of the native mobile application that read data from the online database and displayed statistics on an android application. Matthew recently secured a Reliability Engineer Associate position at the Missiles and Fire Control Branch of Lockheed Martin. He will being working there after graduation.