Energy Sustainable Hydroponics with Automated Reporting and Monitoring

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***Abstract* — The goal of this project is to make an automated hydroponic system that locally displays sensor readings and allow the user to engage automation subsystems through a touchscreen user interface. This system is intended to offload many of the tasks from the user as hydroponics can be an intensive hobby or profession, requiring constant monitoring and care of a setup's parameters. To reduce the cost required to keep the system active, our project is designed for use outside with sustainable energy being harvested from the sun. Data is also collected from the sensors remotely to a server connected on the Local Area Network.**

***Index Terms* — Microcontrollers, Radio Link, DC-DC Power Converters, Solar Energy**

I. INTRODUCTION

The horticulture technique known as hydroponics has had many implications on agricultural science. With its only requisite being the use of any growing substrate other than soil, many variants of hydroponics have been implemented and researched. The plants are typically founded in a substrate, while nutrient-rich water is delivered directly to the roots. This accelerates plant growth because as the roots develop, the increased surface area absorbs the nutrient rich water, allowing for faster growth with time. Indeed, plant biomass and water content is found to be greater in plants grown with hydroponics than those cultured in soil.

Faster growth isn't the only advantage for hydroponics over using soil:

1. Greater Resistance to Pests and Vermin
2. More Biomass
3. Control of Nutrients
4. Easier to Maintain
5. Scalable/Modular

While there are many methods with which to culture plants with hydroponics, our group decided the Nutrient Film Technique (NFT) would be the most appropriate for our project. The NFT method of hydroponics is characterized by a structure which supports the plants as a stream of water with dissolved nutrients, shallow enough for the roots to be mostly exposed to the air, flows over the bottom of the plants' root system and thus compatible with most plant species..

II. OVERVIEW OF PROJECT GOALS

The goal of this project was to develop a hydroponics system which logs sensor data and automates essential processes. Our project will integrate a local interface on the hydroponics system itself to view sensor values and control automation subsystems. The system will also be connected to a Local Area Network to view sensor data and activate automation subsystems remotely. The system being network connected also increases the scalability of the project, as it affords the potential to observe and modify each system from any terminal also connected to the network. With further testing of different plant varieties, profiles can be extrapolated to tailor the system towards a certain species of plant.

III. HYDROPONICS PLATFORM

A suitable platform for testing our electrical system was designed and fabricated using materials that were sustainable, weather ruggedized, and cost effective for our budget. The solution our group implemented was a wood frame with black drainage pipe for the irrigation channels. With this design, there was no need for epoxy or other joining compounds which might be soluble in water, affecting plant growth, and makes for a system less prone to leaks. The nutrient reservoir which stores the nutrient rich water, is a 5 gallon bucket purchased from a local hardware store, found to seal well from the environment and reasonably inert to chemicals.

The water cycle of the hydroponic system involves water being pumped to the highest point and having the water drain through to the reservoir on the lowest layer of the system. Plants are housed in nets pots with a course substrate of clay pellets. The plant root develop around these pellets, forming a stable foundation with the rest of the hydroponic system, their roots growing into the nutrient rich water flowing underneath.

The completed hydroponic system meets our group's requirements for the testing and verification of our electrical and software designs.

Fig. 1. Constructed Test Hydroponic Setup

IV. LOGIC PLATFORM

The electrical hardware for this project consists of microcontrollers to automate the hydroponic test platform using embedded hardware and software design, and power networks to regulate the necessary electrical characteristics for our MCU logic, RF network, sensors, and automation subsystems.

A. Main MCU Board

The main board interfaces all of our different components with the Texas Instruments TM4C1294NCPDT Tiva C microcontroller. It is a separate board from the voltage regulator for a few reasons. These reasons include the ability to power the board from an external power supply or to prevent destroying the components in case the voltage regulators do not work properly. The microcontroller was programmed using the C language in the Code Composer Studio IDE. An in-circuit debug interface built into the TM4C1294 Connected LaunchPad was used to flash the microcontroller using the JTAG interface.

The PCB was designed using Altium Designer and manufactured by OSH Park. It is designed for the LCD touchscreen, sensor hub, pH sensor, dissolved oxygen sensor, and NRF24L01+ wireless module to be directly plugged in as well as giving breakouts for other GPIO pins for added flexibility. The board is a 4.62 x 3.85 inch 4 layer board, using FR408 material, with 2 signal layers as well as a 3.3V and ground plane in between for easier routing of traces from the 128-pin microcontroller. All of the components used are surface mount components and were soldered on with either an iron or hot air gun.

B. MCU Software

The Code Composer Studio IDE by Texas Instruments was used to write code for the Tiva C microcontroller. Multiple libraries from TivaWare were used to facilitate the process of writing the code, including the peripheral library for some of the sensors, the graphics library for our touchscreen, and the sensor library for the rest of the sensors.

Upon power up of the microcontroller program, the different interfaces such as I^2C and 1 wire are initialized for our sensors, SPI interface for the NRF module, as well as the LCD screen and touchscreen interface. The system will then load the pre-defined sensor thresholds and begin to read sensor data. After sensor data has been read, the system then runs in a perpetual loop waiting for a touchscreen interaction which activates an interrupt and runs a function depending on which UI element was touched. Since the LCD hardware is a resistive touchscreen, the interface has intuitive buttons that can be directly pressed on the screen in order to access various functions of the UI. The LCD interface starts out with a display of the menu as well as the current time. The menu lets you access the latest sensor readings as well as any alerts for out of threshold sensor readings. The sensor readings will only update periodically to conserve processor resources, however readings can be manually refreshed. A controls option can also be accessed to turn on various hydroponics components such as the water pump and the nutrition tiller, with states that are saved globally. The NRF24L01 is programmed so that the when data is received, the microcontroller knows through the use of an interrupt pin.

The Beaglebone web server is powered by Linux and receives and transmits the sensor variables and control command signals through use of a web server in conjunction with a custom coded program. [1] The custom coded program is written in C++ and enables communication through a second NRF24L01+ module attached to the GPIO pins of the Beaglebone. The code is compiled using the gcc compiler. The program will continue to run and listen for received communications. If a communication is received, the program writes to a database file with the data it received so that the web server software can parse and display the data. Similarly, if a button is pressed to send a command to the microcontroller, a file is written with a specific keyword that the custom program will read, clear, and then send the appropriate command. Figure 2 shows the different components in relation to each other in the form of a block diagram.

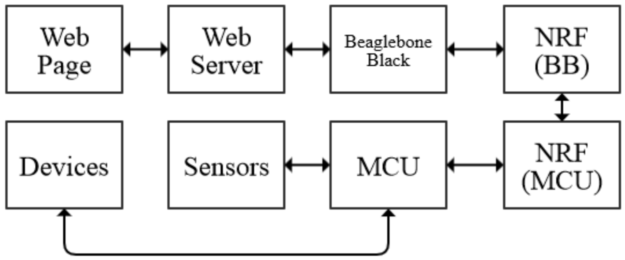

Fig. 2. Webserver Block Diagram

C. Voltage Regulation

One of the major components of our project is the voltage regulator, as it translates voltage from our battery power source into something usable by our microcontroller and sensors. Since efficiency is important with regards to our project, the design will be a switching based voltage regulator which is known for its high efficiency in combination with another switching regulator. [2] The switching regulator circuit will be used for the initial drop in voltage from 12V to 5V for use with the LCD screen, and the second switching regulator circuit will be used to drop 12V input to 3.3V for use with the microcontroller, sensors, and the NRF24L01+ module. Using the powerful WEBENCH tool on TI's web site, it is easy to compare and contrast different designs based on our requirements as well as efficiency, size, and cost.

Using this website, the TI IC model TPS563200 stood out as one of the better options for the first stage switching voltage regulator. It is capable of handling a wide range of input voltages, from 4.5V to 17V, and output voltages, from 0.76V to 7V, as well as having more than enough current for our application. It is also capable of efficiencies that are greater than 90% which is ideal. Two TPS563200 voltage regulators will handle the voltage drops from 12V to 5V and 12V to 3.3V. The following figure, Figure 3, shows the graph of efficiency, taken from datasheets available on the Texas Instruments website for the voltage regulator.

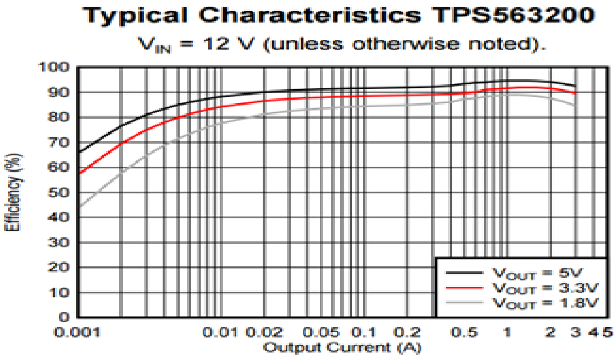

Fig. 3. Efficiency of the TPS563200 voltage regulator with respect to output current and output voltage.

In order to design the complete circuit, two individual circuits are designed so problems can be isolated if any are encountered. The first circuit schematic, shown in Figure 4, is powered by the Texas Instruments TPS563200. The circuit design is based on Texas Instruments reference design and is setup using Texas Instruments recommended components and component values.

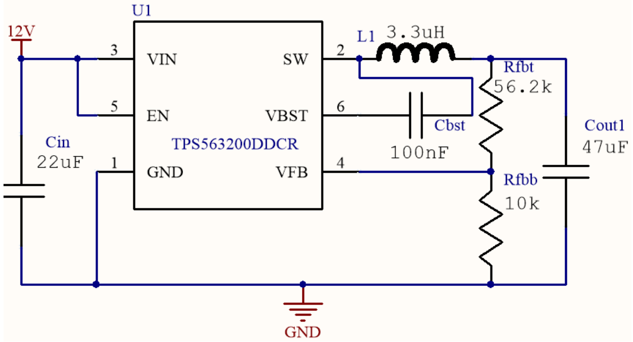

Fig. 4. Schematic for the 12V to 5V voltage regulator circuit

The GND, VIN, and EN pins are the ground, input voltage, and enable pins respectively. The VFB represents the feedback voltage, which controls VOUT with the following equation:

$$V_{OUT} = 0.765 * \left(1 + \frac{R2}{R3}\right) \qquad (1)$$

Where R2 and R3 represent the top and bottom resistor, respectively, of the resistor divider network attached to VFB (Rfbt and Rfbb in Figure 4). VBST powers an internal NFET drive circuit. The SW pin is to connect the internal switching circuitry, which is powered by PWM, to the circuit's inductor, L1. According to the datasheet, a capacitor, Cbst, should connect the SW and Vbst pins and have a 100 nF capacitor in between. Cin as well as Cout are used to prevent sudden changes in voltage. L1 stores the charge necessary for switching voltage regulators to maintain a constant output voltage. Rfbt and Rfbb control VOUT. The values were picked in accordance with the datasheet. Using the above equation (1), VOUT = 5.0643V which is very close to the 5V necessary. This circuit is also capable of providing up to 3A, which leaves plenty of room for our project's current needs.

The 12V to 3.3V circuit is designed similarly. The schematic is identical to Figure 4, with resistor Rfbt being 33.2k instead of 56.2k and the inductor, L1, being 2.2uH instead of 3.3uH which is the value recommended by the datasheet. Using equation (1), VOUT is calculated to be 3.3048V, which is also very close to the 3.3V necessary.

D. LCD Touchscreen

The LCD screen that was chosen for the user interface is the Kentec 3.5" TFT LCD Touch Screen BoosterPack. The touchscreen uses resistive technology to determine where on the screen the user pressed. It also uses an 8-bit parallel interface for faster screen draws than other interfaces. The drawback is the larger amount of pins required from the microcontroller. Because it is a BoosterPack, it interfaces easily with the EK-TM4C1294XL LaunchPad that we chose to prototype the project. The LCD logic board is powered by the 3.3V power supply, however the backlight is powered by the 5V power supply. The LCD has female header ports built-in to easily plug into the BoosterPack XL pins. In order to test the LCD screen functions, TI provides sample code in the form of their grlib_demo program. This program can quickly be compiled in Code Composer Studio and ran after flashing to the LaunchPad device. After flashing and resetting the microcontroller, the LCD should power on and display sample graphics and recognize touch input to the screen to change pages and various markers and sliders.

E. Wireless Modules

A set of 2 nRF24L01+ 2.4 GHz wireless RF transceivers will be used to facilitate communications between our microcontroller and the web server. The transceiver chip is designed by Nordic Semiconductor. Power requirements are low as the maximum current requirement is around 14 mA with a supply voltage of 3.3V. A standby mode is also available which drops the current requirement to 26 µA. Three data rates are available: 250 kbps, 1 Mbps, and 2 Mbps. The data rate that we use for communication is 1 Mbps, which gives better sensitivity than 2 Mbps and lower average current consumption than 250 kbps. The module also supports up to 126 channels, each with a bandwidth of 1 MHz. Configuration of the module is done by writing to various registers over an SPI interface. One of the devices will be connected to the pins of the Tiva C microcontroller while the other device will be connected to the pins of the Beaglebone.

V. AUTOMATION PLATFORM

The processes which regulate the water pump, LED array, nutrient tiller, and water flush system, are all controlled under the automation platform. These automation subsystems are controlled by the main MCU board via opcodes sent to the multiplexing board (MUX board). The MUX board takes 4 analog inputs, 3 for opcode and 1 enable high line, and translates the code against a programmed list of systems to activate. There are sets of solid state relays associated with each automation subsystems, intended to regulate +12V power.

There are two measures of electrical isolation to protect our main MCU board from the higher voltages and currents handled by the MUX board. First, optically isolated solid-state relays to modulate the power being supplied to the subsystems. This is done with an LED and a photosensitive TRIAC, relays using optoisolation are advantageous over a contact relay because LEDs draw less current than contact relay coils for comparable power switching. The second level of isolation provided are diodes integrated on the analog inputs to the MUX microcontroller. Voltages in excess of 40V reverse-bias would need to be applied for the diodes to conduct a current in the reverse direction that would adversely affect the MCU, a fair margin of safety.

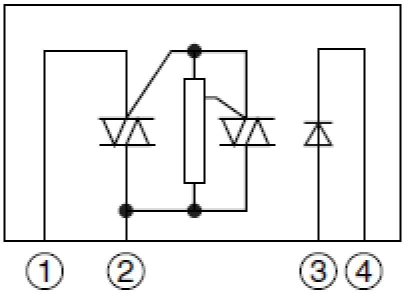

Fig. 5. Diagram of 8A solid-state relay

On our MUX board there are two models of solid-state relays, each intended for different power ratings. The SHARP T108T02 series relays can handle currents up to 8A and AC powered devices, which was an important consideration for testing. The other relay model by IXYS can handle DC voltages up to +60V at 700mA. While not as electrically tolerant, the component is much cheaper than the SHARP relays and their footprint is a third the size. These smaller relays are used to regulate the power to each phase of the stepper motor in the nutrient tiller. To further minimize the amount of cross-cabling across the hydroponic system, the MUX board contains its own 5V switching regulator. Thus, the board only needs +12V power from the car battery to operate the onboard logic and regulate power to the automation subsystems. The only connections that need to be made to the board are 4 analog lines for sending opcode to the MUX board microcontroller and 2 wires going to the +12V power.

A. Water Pump

The water pump is boat bilge pump, selected because it has adequate head pressure necessary to pump water 4ft vertically at 500 gallons-per-hour. Another important characteristic is that it runs on +12V, which is compatible with our existing power distribution and is cheaper that other specialty and hydroponic pumps. The caveat of this pump is the power dissipation is greater, therefore the pump will have a short duty cycle, turning on once every half hour between one to three minutes.

B. LED Array

During the Fall and Spring seasons, it's desirable to have extra lighting for the cultivated plants. An LED array meets this feature, being very power efficient for a light intensity greater than our requirement. RV LED lights were sourced to fulfill this feature because they run on +12V, low-power dissipative, and fairly low-cost.

C. Nutrient Tiller

Upon receiving a command from the MCU, the MUX board will till more nutrients into the reservoir to offload the task from the user. This is useful because during the later stages of plant growth, the amount of nutrient necessary will be greater but must be added in intervals as not to raise the pH value. If the solution were to go too far from equilibrium, the roots would burn and eventually the plants would be killed.

The nutrient tiller adds solute to the reservoir in a principle similar to the Archimede's water screw, a helix translates the solute up a column and into the water contained in the reservoir. This process is done incrementally, so as not to add too much solute which would cause the pH of the system to become out of range.

D. Water Flush System

In the event the pH of the solution goes out of range, it would benefit the hydroponic system more to eject the solution rather than continue to circulate. A 3-way valve actuated by solenoids is connected from the line going from the reservoir to the topmost irrigation channel. These nominally closed water flow solenoids are controlled by the MUX board, actuating whether to route water normally, or flush all of the solution out of the system and alerting the user. When the system is off, these valves are closed and must be initialized by the MCU.

VI. SENSOR PLATFORM

The sensors take measurements of parameters important to the health of the hydroponics system. With these values, the MCU can interpret and respond if necessary by activating one of the automation systems or alerting the user through the local LCD touchscreen. The sensors are calibrated before use to insure the values obtained are accurate. They are polled for data every few minutes to save energy of the MCU and the sensor values change very slowly during nominal operation.

A. pH Sensor

For any agricultural system, the pH level has an important role in the growth and health of the plant within the agricultural system. The parameter pH measures the concentration of hydrogen ions within a liquid solution. This pH level is measured on a scale from 1 to 14, a pH measurement of 7 is said to be neutral, while a pH measurement greater than 7 is referred to as basic, and a pH measurement below 7 is called acidic. In order to properly monitor the pH levels within the hydroponics system, a pH sensor was utilized in the design of the system. After referring to studies done by numerous research groups, the operating range of pH for most hydroponics systems is 5.0-7.5, depending on the plant type. For the autonomous hydroponics system being designed, tomatoes will be used as the base plant type, which require a pH range of 5.5-6.5.

In order to measure the pH levels, for the purpose of autonomously activating the nutrient tiller to add nutrient to the system, or to activate the water flush system in order to create a neutral water environment for the plants. A pH sensor will be used to measure the pH levels, then the microcontroller will use embedded logic to determine what course of action is required, if any. Due to the relatively high accuracy required and the generous funding for Duke Energy in support of this autonomous hydroponics system. A high end hobbyist grade pH sensor was selected, boarding on commercial grade.

Fig 6. pH PCB

The Atlas Scientific pH sensor was selected for implementation into the hydroponics system. This pH sensor is extremely robust, low power, within the budget constraints of this project, and well documented for application execution. The pH sensor comes in two components, the pH circuit shown in Figure 6 and the pH probe, as well as a kit of calibration solutions for initial calibration of the pH sensor. The total price of the pH sensor kit was $149.15, which is understandable on the high end for a pH sensor but well within the sensor budget. The sensor is capable of reading in pH values in the range of 0.001 – 14.000 with a resolution of 0.02 pH.

The operating voltage of the sensor is 3.3V – 5V, which is compatible with the microcontroller selected for the hydroponics system. The pH sensor also operates at 0.995mA at 3.3V, while in in sleep mode, allowing for extremely low power consumption for the majority of the system operation time.

The pH sensor offers two different data protocol configurations, I^2C as well as UART. The pH circuit is by default in UART mode but, through software configuration or hardware configuration the circuit can be used in I^2C mode. For the hydroponics system design, I^2C mode is being used, furthermore the hardware configuration was implemented. To configure the circuit to I^2C mode through hardware, the PGND pin and TX pin shown in Figure 6 were shorted.

The pH sensor will be integrated into the hydroponics system. The values of the pH level will be read by the microcontroller through I^2C protocol. Then within the logic of the embedded microcontroller, an autonomous action will be performed if the pH level is out of the bounds of the user given tolerances. If the pH is too low, nutrient will be added to the water solution within the system by used of the nutrient tiller subsystem. If the pH is too high, the new water will be introduced into the system by use of the water flush subsystem.

B. Dissolved Oxygen Sensor

The dissolved oxygen sensor will provide the hydroponics system with feedback of the quantity of oxygen molecules in the water in which the roots of the plants will be exposed to in the system. Dissolved oxygen is important to the health and growth of the plant life, and is directly correlated with the plant production. The dissolved oxygen within the water solution allows for the plant roots to absorb oxygen, through the roots, and grow more efficiently.

The Atlas Scientific dissolved oxygen sensor was selected for implementation into the hydroponics system. This dissolved oxygen sensor is extremely robust, low power, within the budget constraints of this project, and well documented for application execution. The dissolved sensor comes in two components, the dissolved circuit, which besides the embedded software and PCB silk screen color is exactly like the pH sensor shown in Figure 6 and the dissolved oxygen probe, as well as a kit of calibration solutions for initial calibration of the sensor. The total price of the dissolved oxygen sensor was $257.45, which is by far the most expensive subsystem component in the hydroponics system. The sensor is capable of reading in dissolved oxygen concentrations in the range of 0.01 – 35.99 mg/L with a resolution of 0.02 mg/L. The operating voltage of the sensor is 3.3V – 5V, which is compatible with the microcontroller selected for the hydroponics system. The dissolved oxygen sensor operates at 0.995mA at 3.3V, while in sleep mode, allowing for extremely low power consumption for the majority of the system operation time.

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C. TivaC Sensor Hub

The TivaC sensor hub contains a wide variety of sensors that directly interfaces with the microcontroller being utilized in the hydroponics system. The sensors available on the sensor hub includes, 3-axis gyro, 3-axis accelerometer, 3-axis compass, barometric pressure, humidity, ambient temperature, ambient light, and infrared light. Out of this wide array of sensors, for the purposes of the hydroponics system, the barometric pressure, humidity, ambient temperature, and ambient light sensors will be utilized for plant data information as well as automation logic. All of these sensors can be accessed over I^2C. This sensor hub is provided free of charge from the Texas Instruments Innovation Lab located at the University of Central Florida.

The ambient light sensor used in the sensor hub is the Intersil ISL29023 [3], and is needed to monitor the intensity of light to determine if additional light exposure to the hydroponics system is needed by use of the light array subsystem. The microcontroller reads in the light intensity values every 30 minutes. After averaging those values throughout the day, it calculates the average value of light the plants were exposed to through the day. Then the microcontroller determines if the light exposure is within the given threshold parameters set by the user. If the light exposure was not high enough, the light array subsystem is enabled once the ambient light sensor determines that it is night time.

The barometric pressure sensor used in the sensor hub is the Bosch Sensortec BMP180, and is used to monitor the barometric pressure. The humidity sensor used in the sensor hub is the Sensirion SHT21, and is used to monitor the ambient humidity. The ambient temperature sensor used in the sensor hub is the Sensirion SHT21, and is used to monitor the ambient temperature. These three sensors output their respective sensor readings which are then displayed on the LCD screen of the microcontroller subsystem for data logging. There is no autonomous action taken due to the values of given by the sensors.

D. Water Level Sensor

The water level sensor is needed to monitor the water level of the water reservoir, which the water pump subsystem utilizes. The 12 inch Milone eTape sensor was selected to keep track of the water level. The sensor cost was $39.99, which is well within the budget for the hydroponics system.

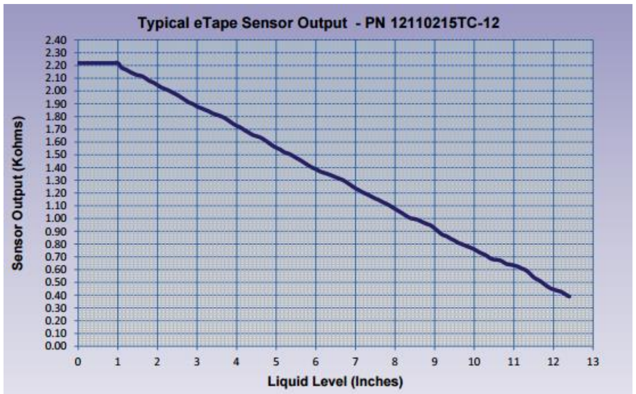

Fig 7. eTape Resistive Output Curve

The water level sensor has a measurement range of 1” – 12”, with a resolution of 0.01”. The sensor is a resistive sensor, resulting in an output reading of 140Ω/inch as shown in Figure 7. The water level sensor has a power consumption of 0.5W. This sensor is used to monitor the water level of the water solution to determine if a water flush or water addition is needed of the hydroponics system, by the use of the water flush subsystem and water pump subsystem respectively. The water level is output to the LCD screen, the user is capable of setting threshold parameters.

E. Water Temperature Sensor

The water temperature sensor is needed to monitor the water temperature levels of the water solution within the hydroponics system, in order to determine if a flush is necessary due to the water temperature levels. For this application the Maxim DS18B20 with a waterproof covering was implemented. The price of the sensor was $9.99, which is by far the cheapest sensor used in the hydroponics system.

The water temperature sensor has a one-wire interface protocol and a voltage range of 3V-5.5V. The sensor has a temperature range of -55◦C - +125◦C, with a resolution of 0.5◦C. The temperature will be read by the microcontroller, if the temperature of the water is too high based on the threshold values set by the user, then the water flush subsystem will be activated. The water temperature is displayed on the LCD screen for the user.

VII. SOLAR POWER SUPPLY

The hydroponics system utilized is 50W monocrystalline silicon solar panel subsystem loaned from the University of Central Florida Senior Design Lab. The solar panel resides outside, and provides power to the charge controller. This subsystem component is the only power source for the entire hydroponics system.

The solar panel charge controller is a rated 100W solar charge controller loaned from the University of Central Florida Senior Design Lab. The charging subsystem has two main functions, the first is to control and regulate charging of the battery bank, the second is to control and regulate the current such that the power is not discharged in the wrong direction. The battery charging subsystem must regulate the electrical current rate to the battery bank and also regulate the voltage level of the charging to the battery bank. If the battery bank is fully charged, the battery charging subsystem must be able to determine that the battery bank is fully and stop charging the battery, and periodically top off the battery bank with power. This is a core feature of the battery charging subsystem.

The battery bank is a 12V 80Ah AGM battery loaned from the University of Central Florida Senior Design Lab. The hydroponics system requires a battery for the storage of solar power charge to be used both during solar panel discharge, as well as night time or overcast daytime when the solar panels are not exposed to sunlight. It is because of this reason, that an over compensated capacity battery was selected for the storage of power for the hydroponics system.

VIII. CONCLUSION

This two-semester design project has been an invaluable conclusion to our undergraduate program at the University of Central Florida. The embedded programming, PCB layout, and other engaging experiences critical to the electrical engineering disciplines that interest us are certain to be invaluable tools during our professional careers. Members have learned how to effectively collaborate to design and implement an exceptional project they are proud of.

ACKNOWLEDGEMENT

The group would like to extend thanks to our project's sponsor: Duke Energy. Their financial support made this project a reality and allowed us to add more to the project than originally planned. Also, we'd like to thank UniKey employee Anders Johansson for his assistance in soldering and troubleshooting our main microcontroller board.

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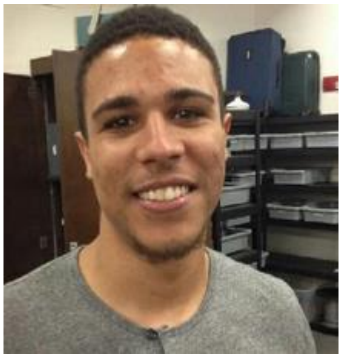
ENGINEERS

David Mascenik is a 30-year-old Electrical Engineering student who is graduating this semester with a Bachelor of Science degree. He is currently working at UniKey Technologies in Winter Park, FL as a Firmware Engineer Intern. David hopes to continue his work with embedded systems programming.

Jon Spychalsky is a 22-year old Electrical Engineering student graduating this semester with his B.S.E.E. He will begin working on his graduate studies this Fall semester.



James Tooles is a 26-year-old Electrical Engineering student who is graduating this semester, August 2015, with a Bachelor of Science degree. James is currently working at UniKey Technologies in Winter Park, FL as an Autonomous Testing Design Engineer Intern. James looks forward to continuing his work in the field of autonomous development