LeafAlone Hydroponics System

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***Abstract* —The objective of this project is to provide a household or "backyard" hydroponic gardening system with a focus on low maintenance, pristine growing conditions, and energy sustainability. The system will monitor plant living conditions and adjust plant pH and nutrient level (ppm) to maintain optimal nutrient uptake by plant root systems. The system will send all sensor data collected during each test over Wi-Fi to a server and database where users can track and change specific system growing conditions. The system shall be solar powered and include an AC wall outlet option as well.**

I. HYDROPONIC BACKGROUND

Hydroponics systems provide an alternative way to grow plants rather than soil based gardening. The essentials needed for plant survival and growth are sunlight, water, nutrients, and oxygen. Hydroponic plants are grown in non-soil mediums while a water based nutrient solution and oxygen are delivered to the roots in different ways. Common hydroponic mediums are Hydroton rocks, which resemble small clay pebbles, and Rockwool, which has a similar consistency as compressed cotton balls. A plastic mesh basket holds the medium and plant root base. The main purpose of the mesh basket and growing medium is to provide plant stability during growth. While soil based plants use their medium for nutrients and stability, hydroponic based mediums provide no nutrients. The plants roots grow through these mediums and are exposed to the nutrients and oxygen they need using different techniques. For this project, a deep-water culture (DWC) hydroponic method was chosen. A DWC design has a very simplistic setup. Plants lie in a plastic mesh basket that contains the growing medium. The plants roots grow through the mesh basket and into an oxygen and nutrient rich reservoir. The reservoir contains a water based nutrient solution. Using an air pump and attaching hose, an air-stone is placed at the bottom of the reservoir to provide constant oxygen into the solution. This air pump runs constantly for multiple reasons. First, to ensure proper plant growth, plant roots need oxygen at all times. Second, the continuous flow of oxygen deters bacteria growth in the reservoir that can lead to root rot and eventually plant death. Each basket is located on the top of the reservoir. As the roots grow into the solution, the plants are able to intake as much nutrients and oxygen that they need. Maintenance on a DWC system requires daily pH and nutrient level (ppm) testing at the minimum. Nutrient testing is performed by using an electrical conductivity sensor to find the Total Dissolved Solids (TDS) in the solution. Fig. 1 below illustrates the basic design.

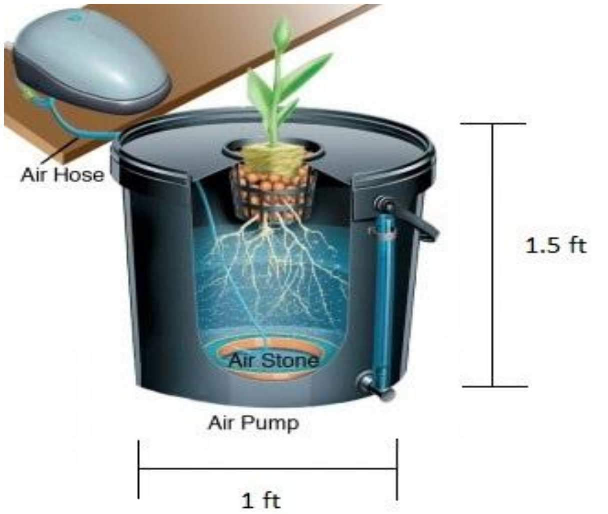


Fig. 1. Example Deep Water Culture Design.

II. INTRODUCTION

The goal of this project was to create a DWC hydroponic system that allows anyone to have the ability to farm their own hydroponic plants using a simple automated system. This system will relieve the user from a lengthy setup and daily maintenance and testing. The user will be able specify the plants wanting to be grown through a web interface which is connected to the microcontroller running the system. The plant specific settings will be loaded and thresholds for each sensor calibrated into the microcontroller, thus eliminating any values needed to be researched by the user. This system will perform all daily testing necessary, adjust system levels (pH, nutrients, water) as necessary, notify the user of a problem requiring action via text message or email, and log all testing data for analysis.

III. SYSTEM COMPONENTS OVERVIEW

The system can be broken into main components that as a whole incorporate all aspects of the project design. Each section is described below with a semi-technical description about their operation and purpose.

A. Plant Reservoir

A company specifically for use in hydroponics manufactures the reservoir chosen for use in this project, and it is well suited to the task of holding water and mounting scientific equipment to. The volume that the liquid reservoir can sustain is up to 20 gallons.

B. Electronics Enclosure

The main functions of the enclosure is to house all of the electrical components, keep them safe and secure from outside interference like shock or weathering, and provide an appealing looking mounting system for the device. For demonstration purposes of the prototype, transparent enclosures have been considered in order to allow people to look at the inside functions of the device as it operates.

The device is mounted onto the side of the plant reservoir and lid structure, with an enclosure containing the sensors overhanging into the interior side of the water reservoir. The lid of the reservoir then folds over to block any sunlight from reaching into the reservoir, which could spur the growth of algae that will harm the growth of the other plants. Fig. 2 below shows an example CAD drawing of reservoir, lid, and enclosure assembly.

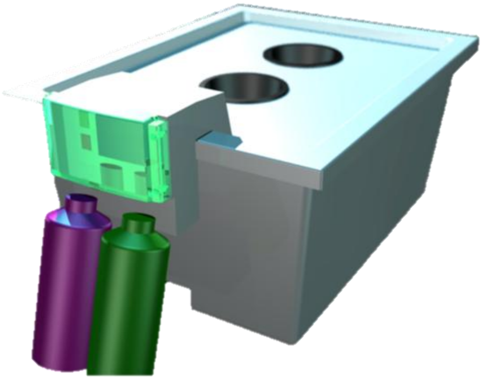


Fig. 2. Prototype Reservoir and Electronics Housing Enclosure.

The main enclosure that has been chosen as a reference to base the prototype enclosure off of is the FIBOX Cardmaster enclosure system. They have built a specialty enclosure system that is designed for use with sensitive lab equipment and instrumentation sensors, which fits the hydroponics system application perfectly. The enclosure is rated NEMA 1, 3, 3R, 4, 4X, 12, 13. In order to incorporate tubing and the sensor probe overhang section, additional plastic will have to be attached to the device, and holes will have to be drilled at various points on the enclosure.

C. Electrical Conductivity Sensor

The electrical conductivity sensor allows the hydroponics device to create routine sensor readings for the total dissolved solids content in the water. This is the primary metric that the device uses to determine when more nutrient solution needs to be pumped into the reservoir where the plant roots are. The reading will first be measured as a current flowing across a sophisticated probe gap, and the total dissolved measurement will be interpreted from the conductivity value based on knowledge of which nutrient solids are being pumped into the device, and how these influence the conductivity of the water.

Like the pH sensor, there is a problem of finding an accurate measurement device that is affordable, reliable over many uses, and that remains accurate even after months of being exposed to the actual water solution. The main method for sensing the TDS of a solution is by measuring the electrical conductivity of the solution and then converting that value into an estimate of TDS using the known nutrients that exist in the water.

The nutrients solution consists of nitrogen (N), phosphorus (P), potassium (K), and many other smaller concentrations of elements such as calcium, magnesium, sulfur, iron, copper, manganese, boron, zinc, molybdenum, and cobalt [1]. The nutrient levels are designed to be balanced so that you can add in a variety of these elements and the plant will respond favorably.

Because this system is designed to be more simplistic for the user, a single commercial nutrient solution is going to be used across all stages of the plant’s growth. This is a commercial solution that can be ordered from any hydroponics or gardening store, and will be added to a refillable container on the actual prototype unit.

After researching the different methods of electrical conductivity measurement, the final EC probe that has been selected is a low cost lab electrical conductivity sensor that is protected with a sheathe of epoxy resin. The particular sensor version that is needed for this project is the K = 0.1 variant, because this probe will operate in drinking water conductivity ranges. The probe cell constant (K) is what determines the conductance measurement of the probe, which is used to obtain the conductivity of the water, according to the formula below.

$$Conductivity = Conductance\ x\ Probes\ cell\ constant\ (K) \tag{1}$$

One precaution to note with the use of the electrical conductivity sensor is that it is an active device that will disrupt the function of other electrically sensitive devices that are operating in the same substance. An easy way to solve this problem is to only run the various sensors one at a time. This is not a problem for the hydroponics design because each sensor reading takes place sequentially.

There are multiple stages that have been designed for the electrical conductivity sensor, in order to interface a conductivity measurement with the microcontroller:

1) Power Enable and Inverting DC/DC Converter
2) Square-Wave Oscillator
3) Trans-Impedance Amplifier
4) Precision AC/DC Rectifier

Due to the nature of the electrical conductivity probe operation, the device must be able to be completely grounded and not output an alternating current signal into the water. The power cannot simply be toggled on and off with the digital output pins of the chosen microcontroller, because the electrical conductivity circuit draws more than the rated maximum voltage of the microcontroller. To solve this problem, a power switching complementary MOSFET layout was utilized, shown in Fig. 3.

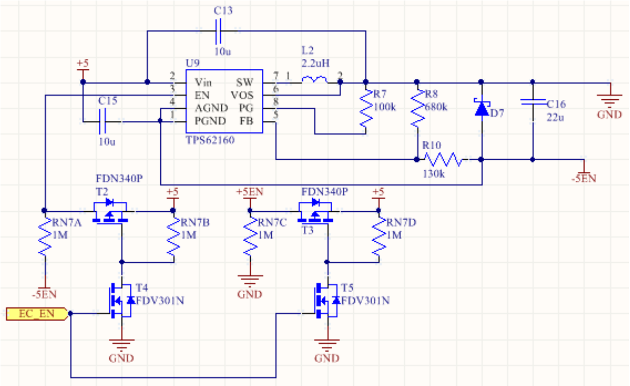


Fig. 3. Inverting DC/DC Converter and MOSFET Power Switching Schematic.

A digital enable signal is sent to two different MOSFET networks, allowing the microcontroller to toggle a positive voltage rail and negative voltage rail at the same time. The other portion of the circuit incorporates a buck/boost DC/DC converter in an inverting voltage layout. The dual MOSFET system is necessary to enable this circuit layout, because the microcontroller cannot otherwise set low the enable pin of the converter, as it is referenced to the negative rail that it generates.

One problem that can be encountered when trying to measure the electrical conductivity of the water is that, when applying a voltage across the probe leads, the ions driving the conductance of the probe will saturate towards one side, creating a capacitive loading affect on the current output of the probe. This problem can only be overcome by taking short timescale measurements, or by sending an AC signal to the probe leads. Fig. 4 shows the AC signal generator that has been incorporated into this design. This signal is then filtered through op amp buffers before it is sent to the probe.

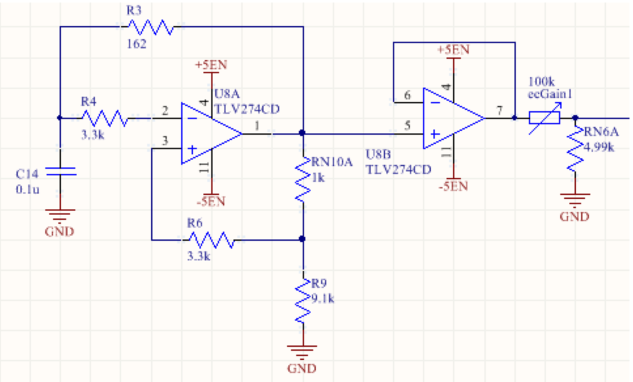


Fig. 4. Square Wave Oscillator and Gain Stage Reduction Buffer Schematic.

The trans-impedance amplifier uses an inverting op amp circuit to obtain a corresponding voltage output from the conductance of the probe. The feedback resistor in this stage needs to be chosen with consideration of the K value of the probe, as well as other qualities of its manufacture. If other probes will be considered with this device, then testing needs to be done to match this feedback resistor with the specific probe. See Fig. 5 below for the amplifier schematic.

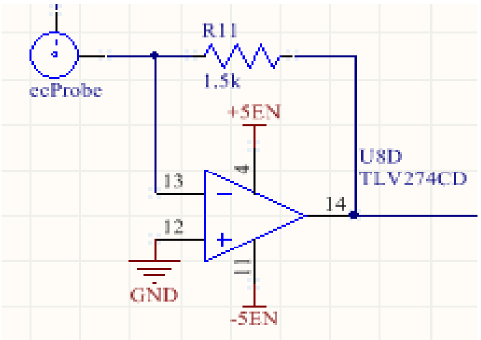


Fig. 5. Trans-Impedance Amplifier Schematic.

The voltage signal at this stage is an alternating signal that has an amplitude which corresponds with the EC of the water. A precision voltage rectifier, sometimes referred to as a super diode, is shown in Fig. 6. This circuit functions on the principal of using a summing amplifier to sum a half-wave rectified signal multiplied by two, added with the original signal. This signal can be further offset with a bias voltage to influence the output voltage DC offset. This is useful for calibrating the probes voltage response. The final voltage signal is now a DC voltage that has a voltage swing of the op amp output, which can be output directly to the internal analog to digital converter of the microcontroller.

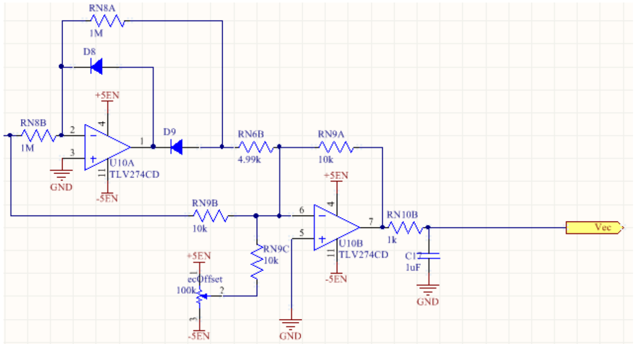


Fig. 6. Precision Full Wave Rectification and Offset Schematic.

D. PH Sensor

One requirement of this automated hydroponics system is to measure and adjust the pH of the hydroponics reservoir. It is important that the pH value stays balanced for a given plant type that is growing in the hydroponics reservoir. The plant will constantly affect the pH, so the system needs to be able to alter the pH of the reservoir using a chemical pH balancing solution. According to research done by numerous people running their own hydroponics systems, the optimum pH range for most hydroponics seems to be within the range of 5.8-6.2 [1]. This allows the plant roots to absorb nutrients at the optimum rate. If the pH level leaves the allowable range that has been decided to be acceptable for optimum plant growth, then a buffering solution is added to affect the pH level, and bring it back within the acceptable range.

In order to know when the pH chemical needs to be added to the hydroponics reservoir, a sensor reads the pH every 25 minutes. Commercial pH sensing devices are too expensive for this system, so a custom sensor needs to be designed. The simplest version of a pH sensor consists of a glass electrode probe that is sensitive to the hydrogen ion concentration, which gives a voltage reading that corresponds linearly with pH. A single junction glass electrode is shown in Fig. 7. According to the Environmental Instrumentation and Analysis Handbook, glass pH electrodes are manufactured by creating a precisely formulated glass matrix gel layer that is welded to an inert glass tube. The potential voltage measured by the glass directly correlates with the pH, with a theoretical response of -59:16 mV/pH [2].

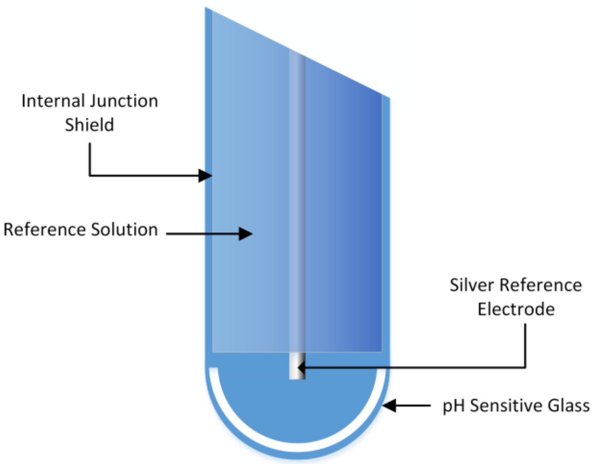


Fig. 7. Glass Electrode PH Sensor Cross Section.

A naive approach to measuring the pH of the water would be to simply incorporate the voltage output of this probe directly into an internal analog to digital converter on the microcontroller, as if it was a simple voltage output. The problem with this is that the probe has an output impedance which is far in excess of any microcontroller input, and even many op amp inputs. The impedance of any pH probe can vary up to the order of 300M ohms, so the output signal must be buffered from the microcontroller with a low bias current op amp. Modern precision op amps are accessible which have input bias currents in the order of femtoamps, and this is an acceptable level to interface the probe with. The isolated sensor circuit used in this design is shown in Fig. 8.

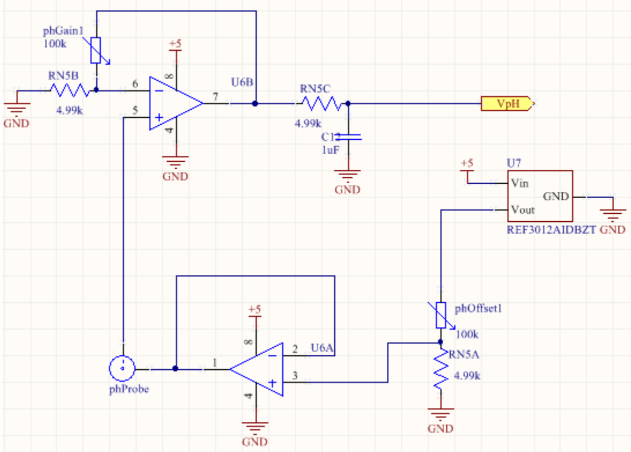


Fig. 8. PH Interface Schematic.

This circuit layout incorporates also a voltage offset to maintain a positive voltage range on the overall signal, protecting the microcontroller from receiving negative voltages on its inputs. Finally, a gain stage brings the 460mV voltage swing of the pH probe output up to 5V voltage swing. This allows the microcontroller to take advantage of the full dynamic range of inputs that it can receive from the sensor. The circuit also incorporates trim pots that are used to calibrate the voltage readings of the probe physically, to maintain more precise pH measurements.

E. Nutrients and pH Management

One of the most important features of the system is the automation of the process where a user would add nutrient or pH buffer solution to the water after measuring these parameters out of an acceptable range. The best way to add liquid solutions to the water reservoir with the control of a microprocessor is to use electrical pumps. Each liquid that needs to be added to the water reservoir will need its own motor so that varying amounts can be added independently.

The principal liquid pump design that has been decided upon for this project is called a peristaltic pump, which can pump liquids and gases in a manner similar to the way that the human digestive system operates. Peristaltic pumps can also work with DC motors, making them easy to interface with microcontrollers and minimally impacting the financial budget.

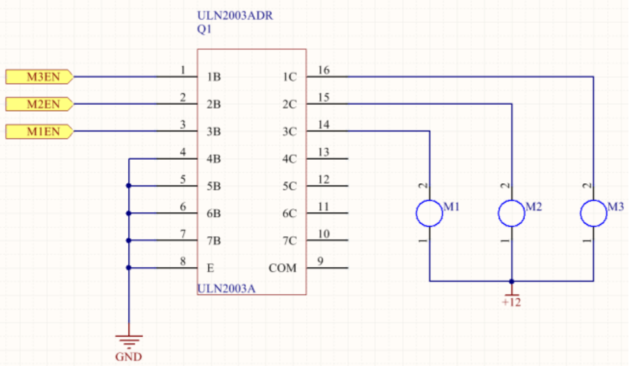


Fig. 9. Motor Control Schematic.

The simplest method of motor control for this device setup is to use a Darlington transistor with protection diodes. This allows the microcontroller to use logic level voltage signals to toggle on and off the motors according to the schematic shown above. The advantage of using this method is that an external voltage source powers the motors with an isolated supply that would otherwise exceed the current limits of the digital pins on the microcontroller. The ULN2003A IC component shown in Fig. 9 is a Darlington Transistor Array that simplifies the footprint of the design on the printed circuit board prototype. The microcontroller outputs to the base, the emitter is grounded, and each motor gets its own collector port for individual control of specific motors.

The installation of these pumps will take place in the device enclosure, next to the other diaphragm pump as well as the microcontroller and sensor printed circuit boards. Clear nylon (or another type of plastic) tubing will run from below the device enclosure, where the containers of nutrient solution and pH buffer are located, up through the enclosure and out into the water reservoir by the various sensors. The tubing will need to go far enough into the water reservoir to not directly affect the sensitive laboratory sensors.

F. Oxygenation Pump and Filter

Another important task that needs to be accomplished in this hydroponics system is to oxygenate the water in the reservoir that the plant is absorbing nutrients from. Oxygen must be present in the water so that the roots of the plant can breathe instead of rotting and preventing the plant from growing. It is necessary in the Deep Water Culture process that this hydroponics system is designed with.

The principal air pump design that has been decided upon for this project is called a diaphragm pump, which can pump gas in a manner similar to the way that lungs operate. Diaphragm pumps can also work with DC motors, making them easy to interface with microcontrollers and minimally impacting the financial budget.

The main components of this subsystem are the diaphragm pump that does the work of pumping the air into the higher pressure of the reservoir, and the air filter and air stone combination device that diffuses the air into the water while also filtering out any undissolved solids contained in the water reservoir.

The diaphragm pump motor will be mounted next to the two peristaltic pumps at the bottom of the device enclosure. A clear plastic nylon tube will need to run alongside the peristaltic pump tubes and be routed into the bottom of the reservoir and in the center where the air filter and air stone is located. The air filter and air stone take this incoming air and squeeze water into the porous filter substance, which causes dissolved air to permeate the water flowing through the filter system. The air filter and air stone need to be mounted as close to the center and under the plant as possible. This will ensure that an optimal amount of liquid is being circulated throughout the device and that enough dissolved oxygen is being added to the water.

G. Water Supply Valve and Sensor

The water level of the hydroponics system is one of the only subsystems in the device that can be controlled easily with purely mechanical means, through the use of valves and drainage holes. The subsystem design is improved with a low cost but reliable water level sensor which will enable the hydroponics device to send the user alerts when the water level becomes to low. This event might occur if the water supply hose became disconnected at some point from the device for an extended period of time.

The water level sensor can either be mounted directly to the reservoir or along with the device enclosure, but it must be physically located at the precise depth that the water should be considered filled to. This would correspond with a liquid volume of about 20 gallons, or when the reservoir itself is nearly topped off.

The water valve must be mounted directly to the water reservoir for the prototype's design in order to simplify the mechanical construction. This is a sacrifice to the overall portability of the hydroponic system, but it is necessary to create a well-designed enclosure. The valve must be installed and sealed properly through the side of the reservoir, and care must be taken to ensure that no leaks are happening so that excess water is not wasted.

H. Printed Circuit Board

The electronics components will all interface directly with an Atmega328p microprocessor, and mount on a main control PCB that is isolated from the power supply. The microcontroller is programmed using the open source Arduino bootloader, and programmable logic is written in C and compiled directly into the 32k EEPROM memory of the microcontroller.

The PCB is manufactured from SunStone Circuits, containing over 80 unique components and over 300 net connections. The final board is mounted with standoffs inside the enclosure, with rugged connectors for the sensors and motors to interface with. The final board is 2 layer, FR4 material, and is 3.915 x 3.119 inches in dimension. Due to the volume of surface mount components, a board stencil was used to lay solder paste on the SMD pads and reflow the components onto the board.

I. Wi-Fi

For this project, the system will use a TI CC3000 Wi-Fi module. The CC3000 is a low cost module that facilitates two-way communication with a hosted web server. The TI CC3000 Wi-Fi module is a wireless network integrated circuit with IEEE 802.11 b/g and embedded IPv4 TCP/IP stack. It can transmit up to +18.0 dBm at 11 Mbps, CCK and has a receiver sensitivity of –88 dBm, with 8% Packet Error Rate (PER) at 11 Mbps. TI CC3000 requires less instructions per second so it can be used with simple microprocessors, and it has small memory footprint. One of the most important stages of building and connecting the Wi-Fi module to the Atmega328p microcontroller was the interface between the two. The method used was the SPI interface. Both the CC3000 and Atmega328p support SPI interfaces, which provided easy two-way communication.

J. Power Supply

The power for the system consists of two subsystems. The two subsystems are AC wall outlet power and solar power that is stored into a battery that provides power to the system. The first option is the simpler of the two. In this configuration, the power will come in from the wall outlet into an AC/DC converter that transforms the 120V, 60 Hertz AC signal into a voltage of 12V DC. The second subsystem for power involves a solar panel and storing the energy into a 12V battery that can provide enough power to the system. A Double-Pole Double-Throw (DPDT) switch is used to switch between the AC/DC converter output and the battery output.

The AC/DC converter was accomplished using a transformer with a 10:1 turn ratio resulting in a step down of 120V to a usable 12V that can power the necessary devices. A full bridge rectifier circuit after the transformer converts the 12V AC voltage to the required 12V DC voltage required for the system. Due to the fact that the transformer is not ideal, a 12V linear regulator is placed after the rectification circuit.

The battery required for the solar power system must be able to withstand a high number of cycles due to daily charging and discharging. The design uses a valve-regulated lead acid battery chosen because of its low cost and reliability. With an air pump (300mA) and microcontroller (200mA) constantly running, it draws roughly 500mA total. Therefore, the minimum capacity for the battery is 5 Ah.

The solar panel used for the system is recycled from a previous senior design project. It was chosen for low cost and is a 50W solar panel with max voltage of 22V and max current of1.8A.

The solar power subsystem requires a charge controller for many reasons including preventing over charging of the battery, impedance matching to get the maximum power from the solar panel to the battery, and controlling the charge current.

The microcontroller chosen for the charge controller was the TI MSP430F235. This microcontroller has 64 total pins, has very low power, has at least 4 analog-to-digital converter pins, and can deliver a PWM signal. Pulse width modulation (PWM) can be implemented by the MSP430F235 using the timer and the duty cycle for the PWM is based on the timer's cycle time, which is changed in the control register for the timer.

The charge controller uses a buck converter to control the voltage coming from the solar panel, which can easily be changed by increasing or decreasing the duty cycle of the PWM signal going into the gate of the MOSFET for the buck converter. In a buck converter circuit, the input voltage and output voltage are directly proportional to each other by the duty cycle of the PWM signal. A circuit diagram of the buck converter is shown in Fig. 10 below where L is an inductor and voltage is applied to the N-channel MOSFET.

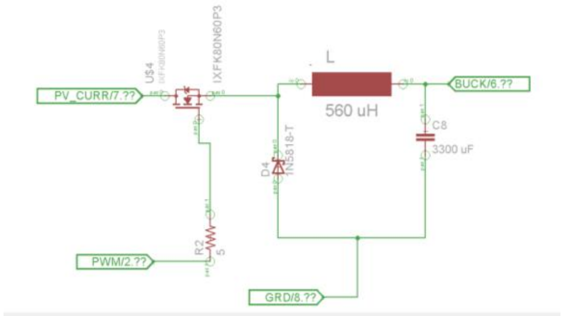


Fig. 10. Buck Converter.

Impedance matching for the solar charging circuit takes measurements of the impedance of the source and the load of the circuit. A current sense circuit is used to get current measurements from the solar panel and battery. This design uses a resistor with low resistance (5 mΩ) that includes a comparator circuit acting to amplify the voltage drop across the resistor to a level that can be used by the analog-to-digital converter (ADC). A schematic diagram of the current sense circuit is shown in Fig. 11 below.

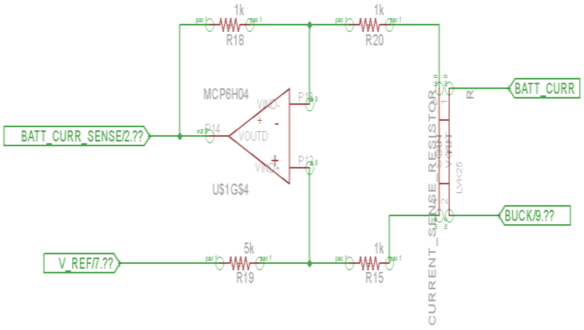


Fig. 11. Current Sensor.

Additionally, when measuring the voltages, the voltage from the source (solar panel) and load (battery) needed to be lowered to a voltage level that is acceptable for the ADC input pin on the microcontroller. A voltage divider was added to the circuit that goes from the source and load voltage into the ADC pin of the microcontroller. The voltage divider can be switched on and off using a MOSFET and BJT combination circuit that is controlled by another output pin on the microcontroller. The reason for the microcontroller's control over the voltage divider is to keep the voltage divider from draining the battery during normal operation. The schematic for the controlled voltage divider circuit is shown in Fig. 12 below.

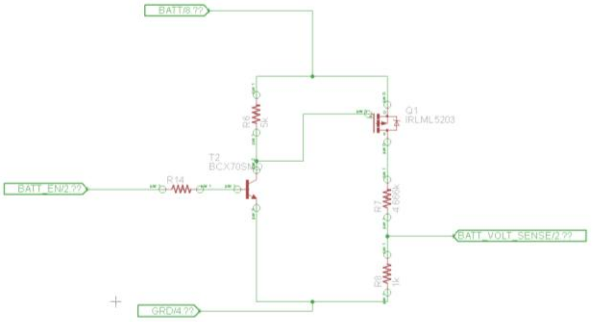


Fig. 12. Voltage Divider Circuit.

K. Software

To program the systems Atmega328p microprocessor, the Arduino IDE 1.0 was used along with Software Serial and String libraries. The microcontroller runs a simple setup that connects to a predefined Wi-Fi network. Once connected, the microcontroller enters a continuous loop as described in Fig. 13 below.

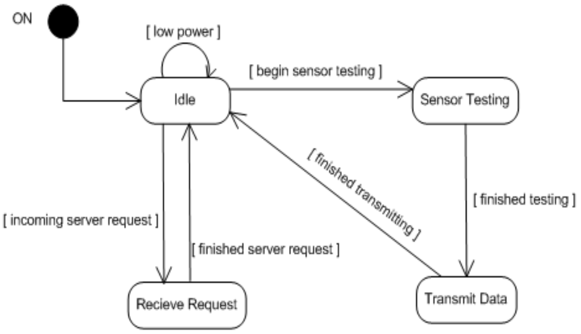


Fig. 13. System State Diagram.

The system will remain idle for 25 minutes in between sensor tests and any incoming server requests. Any incoming server request will not reset the timer. Only after the sensor data has been transmitted to the server will the idle timer be reset. After running the tests, the system will transmit the data to the server and return to the idle state.

For this project, a local server is created and run on a group member's laptop. This server is created using Node.Js which allows for dynamic webpages, and database access all written in JavaScript and HTML languages. Along with the server, a MongoDB database is used in conjunction to store all relevant user, plant, and sensor data. The server handles both user and system requests. User requests are as followed:

1) Login/Logout
2) Register New User
3) Change Account Settings
4) View Sensor Data

All requests coming from the system to the server include sensor data. The server handles these requests by parsing through all sensor data, converting values to industry standards (pH from voltage level to a reading between 1-14 and electrical conductivity transformation to a reading between 0-4000 ppm), notifying the user if the water level is low or if the pH buffer and nutrient liquid containers are empty, and saving all of the sensor data in the database.

IV. CONCLUSION

As the culmination of this two-semester project comes to a close, it has been a great experience. Senior Design offers a real world hands on experiment that gives invaluable knowledge into the computer and electrical engineering fields. Through the research and design, to the actual prototyping of the system, challenges and problems were encountered. In was through hard work, and problem solving that solutions or alternatives were reached. Through this course, members have learned vital teamwork, planning, and engineering principles that they will take with them on future career endeavors.

ACKNOWLEDGEMENT

During this project, the group would like to thank the many people who contributed or helped tremendously. First, a thank you to the group's project sponsor Duke Energy who had helped to extend a financial support for this senior design project. Also, a thank you to the senior design professor Dr. Richie for dedicating his time to help in our project effort. If it wasn't for their support, this project may have stayed a theory and never been a reality.

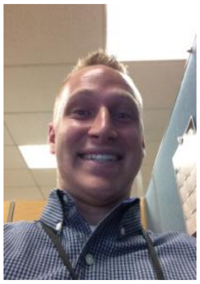
REFERENCES

[1] Alexander, T. and Parker, D. (1994). The Best of Growing Edge. Number v. 1 in The Best of Growing Edge. New Moon Pub.

[2] Lehr, J. H. and Down, R. D. (2005). Environmental instrumentation and analysis handbook / [edited by] Randy D. Down, Jay H. Lehr. Hoboken, N.J. : Wiley- Interscience, c2005.

ENGINEERS

Michael Loomis is a 23-year-old graduating Electrical Engineering student who is current working as a technical intern at Earthrise Space Foundation in Orlando, Florida. Mike hopes to become a design engineer for the space or aeronautical industries.



Matthew DiLeonardo is a 21-year-old graduating Computer Engineering student who is current working in UCF's CWEP Program at Lockheed Martin Missiles and Fire Control (LMMFC) in Orlando, Florida. Matt hopes to become a system engineer for the space or defense industries.

Khalid Al Charif is a 38-year-old originally from Damascus, Syria. He is a graduating Electrical Engineer student who is pursuing his goal of a PhD degree from UCF in the field of RF and microwave engineering to be highly educated and professional in the field of remote sensing and RADAR communications.

Justin Walker is a 26-year-old graduating Electrical Engineer student who has aspirations to land an internship/full time position at a respectable company. Other plans include living in Europe for an extended period of time to be close to his extended family.