SOLAR POWERED AQUAPONICS SENSING KIT

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Abstract

The purpose of this project was to improve the efficiency of the tilapia farming efforts of a small-scale tilapia farm in Kenya by providing frequent and accurate readings of the water quality. To meet the requirements of our consumers, we incorporated a sustainability aspect which was achieved by using 60W solar panels as a power source and a 12V 10Ah battery to power the sensing system overnight. Additionally, we included a button to manually control the pump system and built two status indicators for the sensor system: an LCD screen with dissolved oxygen, pH, and temperature measurements as well as an LED light which illuminated when the sensor values were out of range. We made use of two dc-dc buck-boost converters to both charge the battery and power the pump.

Contents

1. Introduction

This project aims to create an off grid solar-powered pump and water sensing system. This issue was brought to our attention by Professor Brian Lilly. His work with tilapia farming to aid HIV-positive women in Kenya with the organization Living Positive Kenya is what motivated our project. Challenges of this project include: power electronics design for the solar panels and sensor system for aquaponics.

1.1 Objectives

Our goal was to build a low-cost, off-grid solar powered pump and sensor system to use as part of maintaining a multi-hundred-gallon aquaponics system. We are trying to replace manual water chemistry tests with an automated sensor system. Currently, their indoor farming setup has a capacity of about 300 fish per each of their four tanks. The future goals of the farmers are to have 600-900 fish per tank to increase profit margins and provide food for the community.

1.2 Background

To maintain a viable ecosystem for the fish, the water in the fish tank must be tested on a regular basis. Currently, all tests are done manually using chemical test strips. Unfortunately, due to the complexities of maintaining a viable ecosystem for the fish and vegetables, scaling up is not feasible in the current climate. As a result, we are working to develop a kit to monitor the pH, dissolved oxygen, and temperature of the water in each of the fish tanks and easily display the results and notify the farmers that a tank needs maintenance. Currently, measurements must be done by hand with pH testing kits and they do not have similar automated monitoring equipment. The hope is that with an easier way to monitor the status and health of the fishes' environment, low income families/villagers will be able to scale up the amount of fish per tank and the number of tanks overall.

There already exists solutions for hobbyists and industrial scale fish farming. Not only are these industrial sized sensing systems cost prohibitive to a nation whose average yearly income is $1,380 [1], but they are not sustainable. These existing kits either produce fish at a loss for hobbyists or rely on economies of scale to turn a profit at an industrial scale. The goal of our project is to design and build a medium sized aquaponics kit. We believe that we can make a custom solar powered pump system that would be lower cost than commercial fish farming equipment and implement the necessary sensors to aid farmers in monitoring the fish tank.

For our monitoring system, we chose sensors that made sense based on importance for aquaponics and cost effectiveness. We chose to focus on measuring the pH, dissolved oxygen, and temperature of the farming tanks since these are the measurements that are required to be taken most often to maintain proper health of the system [2].

Another one of our objectives was to make this system off-grid such that it is completely solar powered. Current solutions, as mentioned above, rely on AC wall power. This system must be solar powered, as many communities in Africa do not have reliable power infrastructure and it is often unreliable. Since the regions where we are targeting do not have the proper education about the safe disposal of batteries, we had to consider what kind of components would go into our design so that we would only need one relatively small and long-lasting battery per tank. We hope that our final product will be both economically viable and environmentally friendly.

1.3 High Level-Requirements

- Farmers should be able to quickly determine if the levels of the pH, dissolved oxygen, and temperature of each tank are out of range for tilapia.
- Based on hourly dissolved oxygen readings, the microcontroller should trigger the aqua pump to re-oxygenate the water.
- Kit should be completely solar powered.

2 Design

Figure 1 is a description in the form of block diagram for the project. Our design was planned to have two microcontrollers: one for the power supply control and the second for the sensors logic control. The operation of the pump at low dissolved oxygen levels was handled by the power supply control whereas the button, LED, and LCD were all part of the sensor logic control.

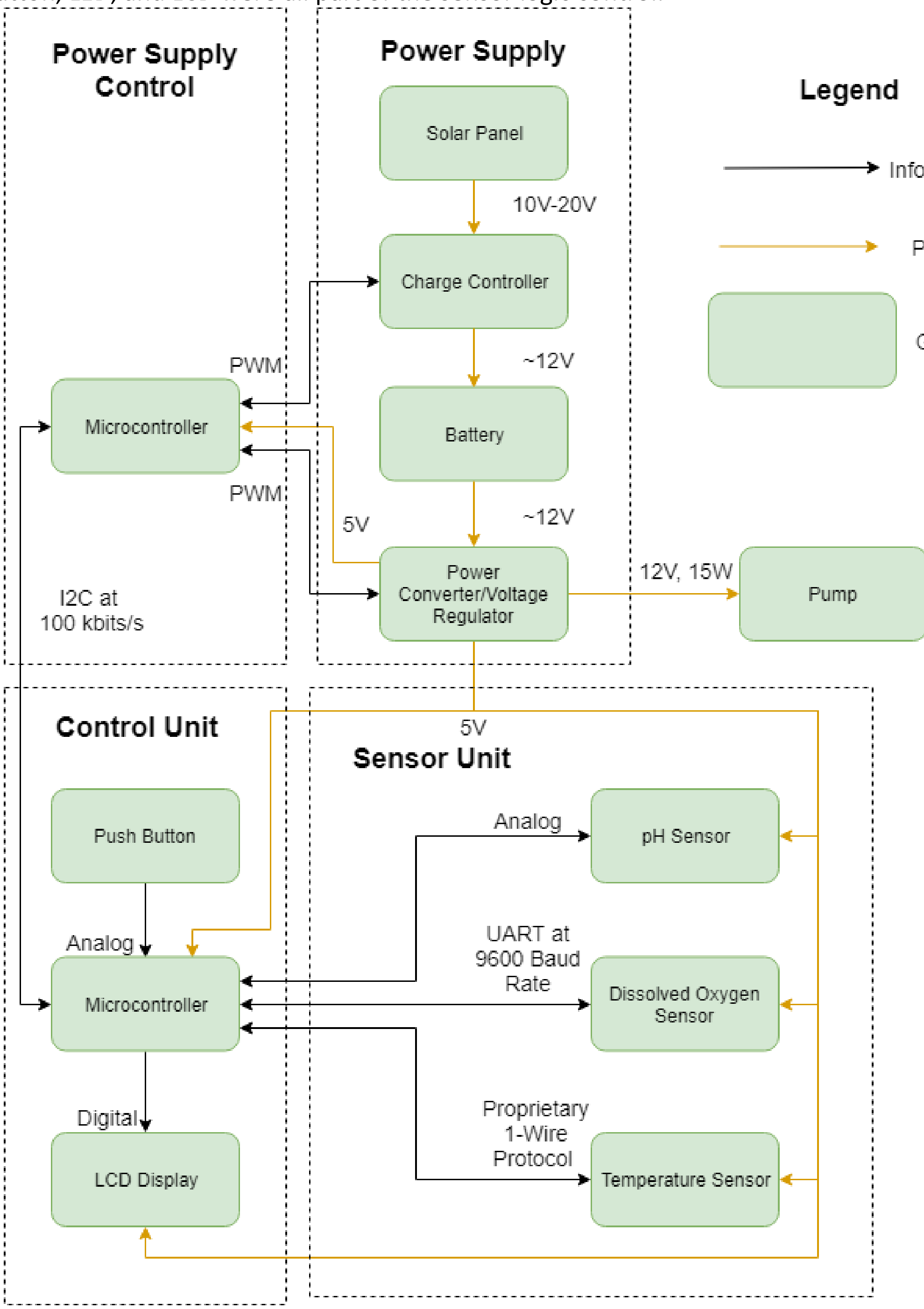

Figure 1: Functional block diagram showing all the necessary components to be implemented

2.1 Power supply

2.1.1 Battery

The goal when choosing the battery for our system was to find a balance between safety, cost, and energy requirements. First, we considered the types of batteries that were acceptable for our use since we needed to be constantly charging and discharging the battery throughout its lifetime. From this, we determined that we would use a lithium-based battery since lead-acid batteries were not recommended by the course staff. Additionally, the large amount of lead and sulfuric acid within the battery would not make it suitable for a country like Kenya with limited infrastructure of battery recycling [3]. From there, we determined what our minimum battery capacity requirements were assuming a best-case scenario. Since we already knew that our whole system would be running in dc voltage, our calculations were simplified between finding the wattage required to run for 4 continuous hours and finding the suitable amp-hour requirement for our 12V system.

The dc pump that we were considering was rated at 13.2W and 12V. The Atmega328P, of which we had two, required 0.16W to operate. We will include a multiple of 1.2 to account for the power draw of the LCD display, IC and LED. We also want the battery to never hit the deep discharge region (30% of maximum charge) to prolong the lifespan of the battery. See Equation (1) and (2).

$$\frac{1.2 \times (13.2W + 0.16W)}{0.7} \times 4h = 91.61Wh \tag{1}$$

$$\frac{91.61Wh}{12V} = 7.63Ah \tag{2}$$

We've determined that we will need a battery that has a capacitor of at least 7.63Ah. From here we settled on the Dakota Lithium LiFePO4 12V 10Ah battery to fit our needs. This extra capacity will give us some extra power for days with little to no sun.

2.1.2 Solar Panels

Our sponsor gave us the option of using between one to three 20W rated panels. Since we wanted to be able to charge the battery enough during the day so that it could run without interruption overnight, we chose to use the 60W combined configuration so the battery could reach full charge during the day even with the system in use.

2.1.3 Dc-dc Converter

Our charge controllers were designed to be cascaded into one another to simplify the circuit operation. Since the solar panel was to act as our only power source, we had to consider that during overcast operation, the panel's output voltage could drop below 10V and that at full-sun, the panel might output upwards of 20V. For this reason, the buck-boost converter topology was chosen since the battery needed an input of 14.8V to be in the charging range and the water pump needed an input voltage of 12V to be running at it maximum flow rate.

Figure 2 depicts how the solar panel (depicted as an ac voltage source even though it is dc), outputs to the battery, BT1. From there, the battery is now the 'input' source to the output that is the 12V dc motor.

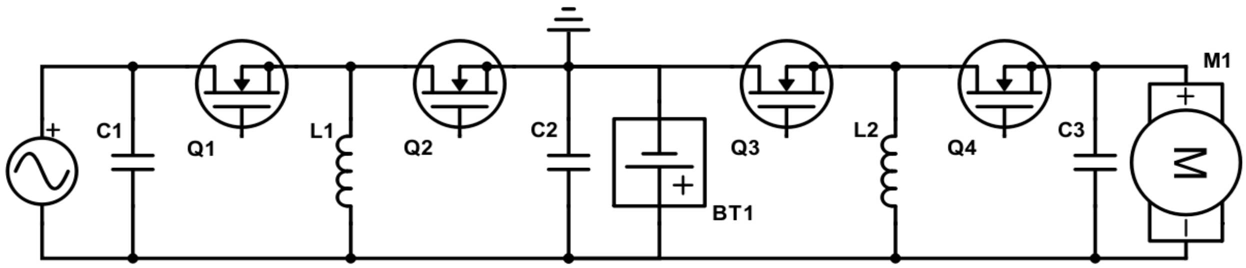

Figure 2: Charge Controller Circuit Diagram

2.1.4 Pump

We chose the Aubig 12V DC Brushless Water Pump [4] to use as our water aerator due to its pump capacity, voltage and current requirements, and cost. The decision to use a 12V pump stemmed from the fact that we considered using a 12V battery to power our system and we wanted to match their voltages. Additionally, a stronger pump would significantly increase the cost. The 12V pumps that we were considering had a 16ft vertical water ejection height which would've been more than enough to aerate the tilapia tanks. The decision to use a dc brushless motor also meant simpler pump controls without the need to build our own inverter to drive the pump.

2.1.5 Microcontroller

We chose to use the ATMega328-PU for our project for ease of use. With no embedded systems experience, we decided to choose a microcontroller that provided many libraries and resources. It was also a good option for prototyping and debugging, as we would start on the development board and later migrate to a breadboard. We had considered using the ATMega2560, however we determined we did not need the additional processing power and I/O that the 2560 provided.

We initially designed our system to use a single ATMega328. However, we quickly determined that we would need at least one additional microcontroller, as we did not have enough I/O on one two handles both the sensing subsystem controls and the power subsystem controls. We opted to use two ATMega328s instead of upgrading to a ATMega2580 to maintain as much modularity in our system as possible. Later in the project, this served us particularly well as we could demonstrate each subsystem individually with ease.

We later integrated one more microcontroller to our system much later in the timeline. This was due to PWM signal generation. The ATMega328 has three internal timers, with two that supposedly were available for use. We found problems generating two different PWM signals with different frequencies using a single microcontroller. Addition of a second signal to our first signal interfered with the first. As a quick solution to the problem, we used an additional microcontroller to generate the second signal. In our final design, we repurposed an extra PCB from the sensing subsystem for this second microcontroller.

2.1.6 pH Sensor, Dissolved Oxygen Sensor, Temperature Sensor

The pH, dissolved oxygen (DO), and temperature are three pillars of aquaponics that are essential to the health of the system [5]. The health of the fish is most sensitive to these three criteria. Many aquaponics resources recommend checking the pH levels at least 3-4 times per week - our sensors alleviate the farmers of the need to physically go to each tank and make these measurements. The best growing conditions for tilapia are between a pH level of 7.0-7.5 [6]. Therefore, if the hourly measurement indicates a pH reading outside of this range, the LED indicator at the top of the sensing kit will glow red and the LCD display will read GOOD, OK, or BAD.

We chose the DFRobot SEN0161 as our pH sensor since it was lab-ready with a sub-$30 price tag. There were also resources available online to assist us with programming the sensor with our microcontroller [7]. Next, we decided on the Atlas Scientific Dissolved Oxygen probe. At a price of $249.95, this was a hefty price to pay. However, the price of this sensing probe was not as steep as some other options. Additionally, it came with its own ADC circuit, BNC connector, and was UART compatible [8]. For our purposes, this dissolved oxygen was a good fit since it could be indefinitely submerged in fresh or saltwater. For the last sensor, we went with the DS18B20 Waterproof Sensor from SparkFun due to reports of its accuracy, ease of use, low price point, and waterproof abilities [9].

2.1.7 User Interface, Push Button and LCD Screen

Our goal for the user interface was to display current values of pH, temperature, and dissolved oxygen, a LED indicator signaling out-of-range values, and a button to trigger pump operation. We opted for a standard 4x20 LCD for our display and a simple push button which we used a software debounce to eliminate the need extra PCB design and space.

The push button used to trigger the pump sends a digital high signal to our third microcontroller, which was used to generate the PWM signal to our second converter which had an output of 12V. Upon receipt of the digital signal, the microcontroller would adjust the PWM signal accordingly to turn the pump on and off by turning the 12V converter on and off.

3. Design Verification

3.1 Solar Panel

On April 20, 2018, our group performed our solar panel testing verification. As per our Design Document, our goal was to be able to achieve at least 40W at a minimum of 12V during full sunlight. Due to the limitations of Champaign-Urbana, Illinois weather, we were never able to perform panel testing during a fully sunny day. The results in Table 1 and 2 are based on an overcast day while operating all three of the 20W solar panels in parallel.

Table 1: Solar panel verification with panels face up on ground

Resistance (Ω)	Voltage (V)	Current (A)	Power (W)
14.1	18.7	1.32	24.68
11.8	18.0	1.53	27.45
11.1	17.9	1.61	28.87
10.5	16.5	1.57	25.90
9.3	15.4	1.66	25.48
7.1	12.8	1.80	23.04
5.3	10.0	1.89	18.86

As the data in Table 1 shows, we were not getting close to our 40W requirement. We attributed this fact to the overhead clouds and that we were laying the panels face up and flat on the ground. Table 2 shows an improvement in the power generation especially at lower loads.

Table 2. Solar panel verification with panels perpendicular to sun

Resistance (Ω)	Voltage (V)	Current (A)	Power (W)
13.5	19.0	1.41	26.74
11.4	18.5	1.62	30.02
11.1	19.0	1.72	32.80
9.6	18.2	1.89	34.50
8.0	17.4	2.18	37.85
5.8	15.0	2.59	38.79

Although we were not able to get a reading of 40W, we consider that passing our requirements due to the inclement weather. Additionally, the UV index in Champaign, IL during winter months is significantly less than Kenya’s year-round, which is closer to the equator and has a sun angle closer to 90°. Operation in Kenya should be closer to the rated 60W of the solar panel system.

3.2 Dc-dc Converter

There are two dc-dc converters we needed to verify. The first converter needed to be able to output around 14.8V from an input of 10-20V at 60W. Figure 3 shows a typical output waveform generated using the lab bench waveform generator as the PWM input.

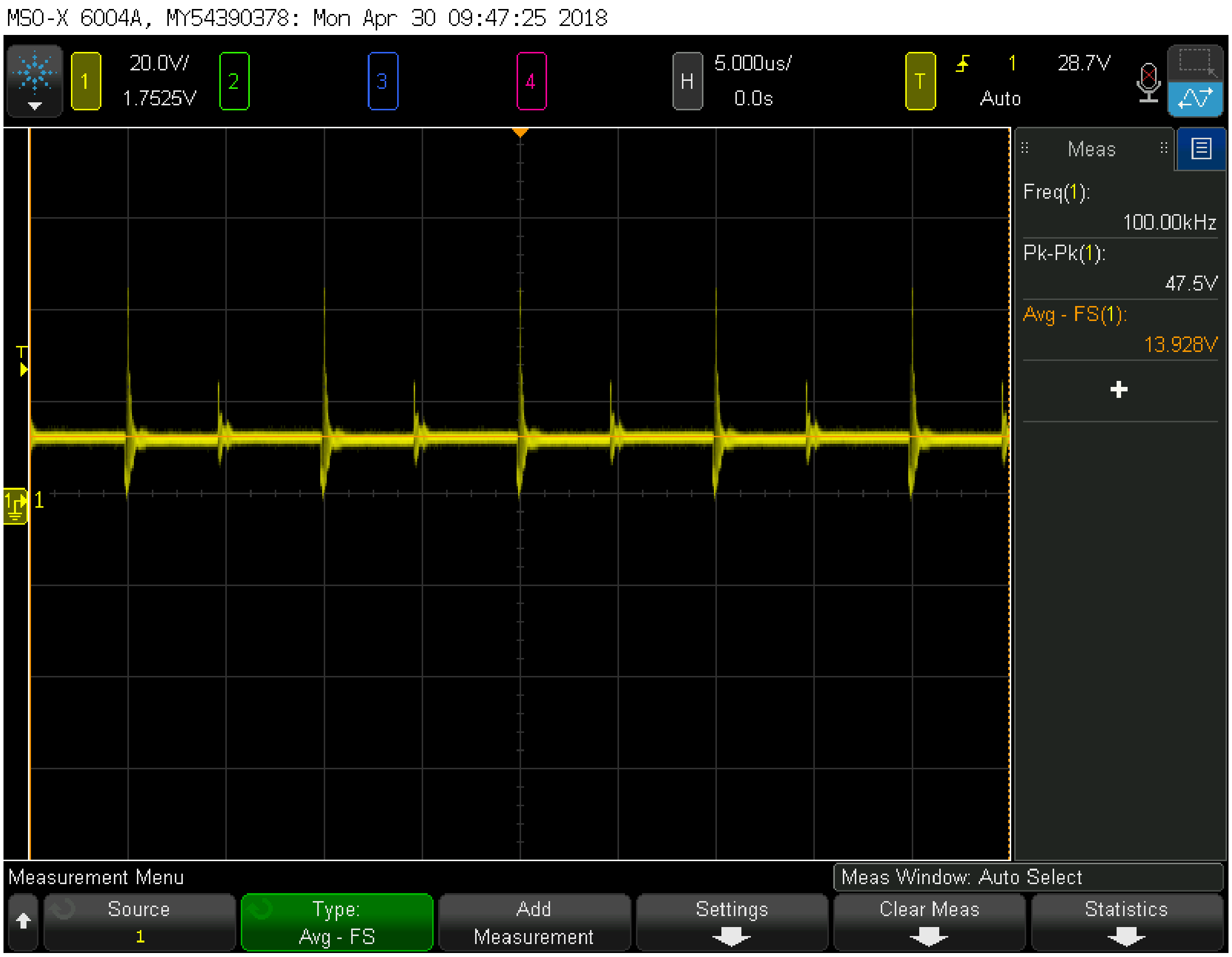

Figure 3: Output waveform of first converter

We see that our output average voltage is within tolerance range for our verification requirements.

The second converter must be able to output around 12V at an input of 11-14.8V at 13.2W. Figure 4 shows one trial of the second dc-dc converter.

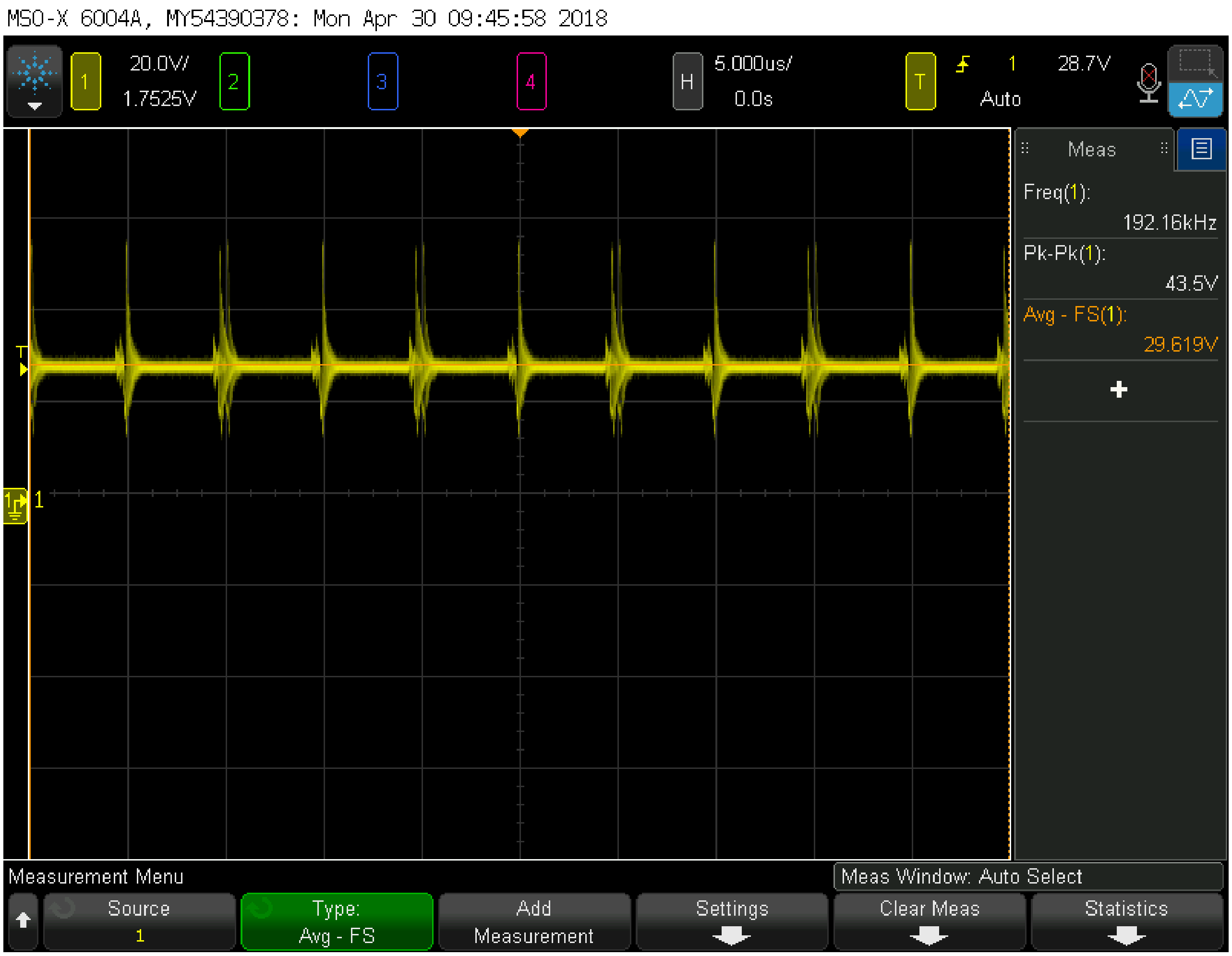

Figure 4: Output waveform of second converter

The above waveform is referenced to ground which mean to determine the actual voltage, we will need to perform KVL using the circuit diagram in Figure 2. By subtracting the battery voltage from the output voltage in Figure 4, we find the pump voltage to be around 14V. After a few more trials of refining our required duty ratio, we met our requirement of 12V output.

We also see a lot of switching noise in our converter output waveform. These spikes in voltage are caused by stray inductance in our wires but does not affect the verification of our requirements. Our battery and pump are not sensitive to these voltage spikes and therefore will perform up our requirements regardless of these noisy output waveforms.

3.2 Pump

Our pump was first tested in an isolated manner from our system. We verified that it met our specifications of being able to pump water to a minimum height of 0.5 meters with a 12V input voltage.

3.3 Microcontroller

Three ATMega328s were used in our project. All three were verified in a similar manner. We initially programmed a microcontroller with a simple program using the Arduino Uno board. We then implemented a similar circuit on a breadboard with an external crystal oscillator and connected the pre-programmed microcontroller to the circuit. From there, we power the system and confirm logic was correct. Similarly, we confirmed that PWM signals generated by the microcontrollers were consistent with those we desired by monitoring the signal on the oscilloscope.

3.4 pH Sensor, Dissolved Oxygen Sensor, Temperature Sensor

3.4.1 pH Sensor

The pH sensor was the most difficult sensor to calibrate. Calibration was done by using a base solution with neutral pH (a pH of 7.0). We acquired a small amount with our sensor kit in the cap of the probe and used this to determine the calibration value. However, calibration needs to be performed each time the sensor is used. This is unrealistic for a number of reasons. First, the values used in data collection rely on the calibrated offset. Second, we would need readily available base solution to perform the calibration. During our calibration, we had contaminated our original solution by submerging the probe in a different solution to test the probe, as we have to replace the cap on the probe when complete. In a laboratory setting, performing this procedure is simple. However, our system is designed to be standalone and it is unreasonable to make code changes.

As a result of the difficulty in calibration, we found that some solution readings were more accurate than others. To ensure our sensor was working properly we purchased buffer solutions with a known pH to test on. For lower pH values, the sensor was more accurate and within 0.3 pH units. For the higher pH solution, readings were off by almost 2 pH units. On average error, we deemed this acceptable for the purpose of our project.

Additionally, we learned after ordering our sensors that the probe we chose was not designed for long-term submersion. The temperature and dissolved oxygen probes were designed for indefinite submersion in water, however the pH sensor was not. For the purpose of our project, this probe served us well.

3.4.2 Dissolved Oxygen Sensor

Since the motivation behind this project was to be able to accurately and easily measure various conditions of the water in the tilapia farm, a tolerance analysis was performed on the most expensive sensor that would be used: the dissolved oxygen sensor. This sensor is the most expensive single component in our design so we chose to test its accuracy and gain further familiarity with it. Additionally, the results obtained by the DO sensor would be crucial to our logic for controlling when the water pump turns on and off during the daytime and at night. As such, the reliability of this sensor is of utmost importance such that we do not drain the battery of our solar-powered system.

The galvanic dissolved oxygen probe consists of a polyethylene membrane, an anode, and a cathode. The oxygen molecules in solution cross through the membrane and are reduced at the cathode where a small voltage is produced. The more oxygen that is present in solution, the more mV output there is. The DO sensor can also be used to detect the oxygen content in gases. This principle is useful when solving for our dissolved oxygen saturation level. Equation 1 is used to convert the measured voltage in water to a percent saturation. From there, the mg/L of DO in water can be found by referencing a solubility table (Figure 5).

$$Saturation\ (\%) = (mV\ in\ H2OmV\ in\ air) * 100 \tag{3}$$

The DO sensor detected 47 mV in the air. We took the measurements listed below in Table 1. The water was sourced from a water fountain and the sink in the ECE 445 Senior Design lab.

Table 3. Testing of Dissolved Oxygen Probe

Test Number	Source of H2O, Amount Shaken (sec)	Voltage in H2O (mV)	Dissolved Oxygen Saturation (%)	Dissolved Oxygen (mg/L)
1	Fountain, 0	25	53.19	5.84
2	Fountain, 5	31	65.36	7.24
3	Fountain, 25	42	89.36	9.81
4	Fountain, 0	30	42.55	4.67
5	Fountain, 5	33	70.21	7.71
6	Fountain, 25	43	91.48	10.04
7	Sink, 0	17	36.17	3.97
8	Sink, 5	40	85.10	9.34
9	Sink, 25	45	95.74	10.51

Ultimately, we gathered that the dissolved oxygen sensor is precise enough such that it detects oxygen added to water by disturbances. It verifies our oxygenation method's effectiveness in producing discernible changes in dissolved oxygen concentrations. Given these observations, we can verify that our sensor is effective and stays within tolerance given controlled operating temperatures.

Furthermore, when we placed the dissolved oxygen probe into deoxygenated solution (0.0 mg/L). Our LCD screen measured 0.4 mg/L. This measurement confirms that our dissolved oxygen reads considerably close to what the actual readings are.

3.4.3 Temperature Sensor

We verified our sensor, DS18B20, against a Harbor branded food thermometer. Consistently the results were within 2° Celsius. This met our requirements from the design proposal.

3.5 User Interface, Push Button, LCD Display

Functioning microcontroller logic corresponded with a functioning sensing control unit. Out of range values ("BAD" indicator label on the LCD) corresponds to the indicator LED illuminating. Pushing the button sends a signal to our third microcontroller, which in turn would control the PWM signal to our second buck converter. Confirmation of this was made by monitoring the PWM output and voltage at the output of the 12V converter.

4. Costs

4.1 Parts

Table 4: Solar panel verification with panels face up on ground

Part	Retailer	Cost	Quantity	Total Cost
Solar panels	Amazon	33.99	3	101.97
Temperature sensor	Sparkfun	9.95	1	9.95
Dissolved oxygen kit	Sparkfun	249.95	1	249.95
pH sensor	DF Robot	41.50	1	41.50
LCD Display	RioRand	7.99	1	7.99
12V, 10Ah Battery	Amazon	114.00	1	114.00
Buttons	Amazon	8.99	1	8.99
Microcontroller	Amazon	16.99	1	16.99
INA226 Current monitor	Mouser	3.30	2	6.60
PSJ2N Resistor	Mouser	1.45	3	4.35
STTH1502 Diode	Mouser	1.80	3	5.40
MUR1520G Rectifier	Mouser	1.08	3	3.24
Connectors, header pins, screws	ECE Store	14.66	1	14.66
Heat sinks, voltage regulators, header pins	ECE Store	2.91	1	2.91
DC Pump	Amazon	22.99	1	22.99
Power monitoring IC	Amazon	12.00	2	24.00
Crystal oscillators	Amazon	5.00	1	5.00
Voltage regulators	ECE Store	4.58	1	4.58
Arduino, regulators, power monitoring ICs	Amazon	40.00	1	40.00
Plastic tubing for pump	Lowes	5.00	1	5.00
Voltage regulators	ECE Store	4.08	1	4.08
Total				**694.15**

4.2 Labor

Table 5: Solar panel verification with panels face up on ground

Name	Hourly Rate	Hours per Week	Cost for 16 Weeks x 2.5
Shannon Kuruc	30.00	15	18,000.00
Emily Wang	30.00	15	18,000.00
Tony Xiao	30.00	15	18,000.00
Total			**54,000.00**

5. Conclusion

5.1 Accomplishments

Over the course of the semester, we made large strides towards making a fully sustainable and working product. In the end, we successfully implemented the complete sensing subsystem and user interface. By completing this, the module can display current sensor readings clearly on the LCD and illuminating indicator LEDs when values are out of range.

Additionally, we also implemented our two DC/DC converters and pump control logic to trigger our 12V DC pump when dissolved oxygen readings are out of range for the system. We ran into difficulties when transitioning from breadboard to PCB, however the system was fully functional on a breadboard.

Additionally, we were able to successfully verify each of the independent requirements that we had set from our Design Document.

5.2 Uncertainties

One major uncertainty is the functioning of our integrated system with solar panels as a power source. We tested both systems individually - the solar panels with a simulated load and our overall project with a simulated source. However, due to time limitations and weather limitations, we were unable to test our integrated product. Impedance matching between our panels and our system was a concerned raised during design.

5.3 Ethical considerations

5.3.1 Safety

Our project is designed to take measurements from a large tank of water. There are inherent safety concerns with any type of electronics equipment in water, including but not limited to moisture damage to components or electrocution.

There are a variety of hazards associated with lithium-ion battery use. This includes overcharging, overheating, and mechanical abuse [10]. Overcharging is the most serious hazard, however it is the least likely. We would need to implement safeguards such as an automatic shut off when the temperature is too high. We also need to consider mechanical abuse, as your average Kenyan does not know proper battery safety and disposal. Lilly expressed his concerns with batteries, however it is necessary for our project and the Living Positive Kenya facility is a controlled environment.

Generally, we are concerned with the impact of electronic equipment being disposed of improperly and toxins making their way into the environment. This potentially violates IEEE Code of Ethics #1: “to hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, and to disclose promptly factors that might endanger the public or the environment”.

5.3.2 Ethics

A potential concern is with introducing this equipment is damage to the environment and people. IEEE Code of Ethics 7.8.5 states that the intent is “to improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies, including intelligent systems;”. Our intention is to empower and support individuals in their health. Introducing lithium ion batteries potentially violates 7.8.1 of IEEE Code of Ethics in terms of sustainability.

There are also ethical concerns with animal farming of any sort. However, our intent is to build a system that supports sustainable, humane farming to serve a group of people in need.

5.4 Future work

A point for future work is the controls for the power electronics. Our controls were very simplified, as none of our team members had control systems experience. We had decided on digital controls, however it could be beneficial to look into analog controls. We also encountered problems during system integration with our converter controls, as the behavior was inconsistent with behavior of our system on the breadboard.

Another component that could be improved upon is the voltage and current sensor integration. Our implementations were restricted by time, as we used trial and error in our design.

One component that was out of scope of our project was a maximum power point tracking system. This would improve the efficiency of our system and extend the operation time by charging the battery more quickly and providing the optimal voltage more consistently. Unfortunately, we were not able to explore this avenue as much as we would have liked due to the very cloudy and rainy weather that we experienced throughout March and April.

The last area of improvement that we would like to see would be of the converter ripples. We observed that there was excessive ringing in Figure 3 and 4 due to the large inductances. In the future, we would consider using a different topology in order to minimize the ringing and the losses in the system.

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Appendix A Main Subset of R and V Table

Table 6 System Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
Solar Panel must provide at least 40W at a minimum of 12V full sunlight*. *Note that the UV index in Champaign, IL during winter months is significantly less than Kenya's year-round, which is closer to the equator and has a sun angle closer to 90°.	1. Place solar panel flat on the ground during full sunlight. 2. Using a multimeter, record the voltage across all 3 panels in parallel using a variable power resistor rated 1-25Ω. a. Perform resistive load sweep on maximum of 5Ω intervals. 3. Check results to ensure that ~40W of power is capable of being delivered at some power point of the solar panel.	Y
1st Converter: Input: 10-25V at 30W (simulates solar panels at inputs) Output: 14.5V +/-10% at 43.5W +/- 10% (simulates lithium battery) 2nd Converter: Input: 11-15V (output of lithium battery) Output: 12V +/-5% at 15W (DC pump)	14.5V converter: 1. Attach a 30W load. 2. Connect oscilloscope across the load. 3. Input 14.5V DC to regulator. 4. Ensure output remains between 14.5V +/- 10%. 12V converter: 1. Attach a 15W load. 2. Connect oscilloscope across the load. 3. Input 12V DC to regulator. 4. Ensure output remains between 12V +/-5%.	Y
Read and interpret sensor data, relay info to UI, and send control signal to pump and display. Must be able to send data through UART at a Baud Rate of 9600. The second microcontroller must be able to output a PWM signal.	UART verification: 1. Connect the microcontroller to a serial terminal. 2. Set the Baud rate to be 9600. 3. Send and echo back a string of 100 numbers 4. Check that numbers match what was sent. PWM: 1. Connect the output of the PWM generator pin to an oscilloscope. 2. Set the duty ratio of the PWM to be 50%. 3. View and verify that the duty ratio is 50% on the oscilloscope.	Y