X-HAB
Technical Memorandum

CU Boulder

June 11, 2014

Abstract

The X-HAB team in the CU Graduate Projects course was tasked with developing a Distributed Robotic Plant Production System (DRoPPS) that provided remote food production capability for long-duration space missions. The system consists of a Remotely Operated Gardening Robot (ROGR) and a Smart Pot (SPOT). SPOT was designed to grow a plant in a hydroponic system, while also providing multiple sensor data feedback to a remote user. ROGR was designed to give a remote user a method of moving SPOT and caring for the plant. A User Interface (UI) was created to provide a means by which a remote user could interact with the system. At the conclusion of the semester, ROGR was 95% complete, and only required minor mechanical fixes. SPOT was 85% complete, and required additional machining of mechanical parts. The UI was 75% complete, and required additional functionality and user testing. The project was not fully completed due to the scope of the project. Regardless, multiple team members have agreed to continue working on the project to finish by the June 1st presentation day at NASA.

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1 Introduction

The X-HAB team in the CU Graduate Projects course was tasked with developing a Distributed Robotic Plant Production System (DRoPPS) that provided remote food production capability for long-duration space missions. The system consists of a Remotely Operated Gardening Robot (ROGR) and a Smart Pot (SPOT). SPOT was designed to grow a plant in a hydroponic system, while also providing multiple sensor data feedback to a remote user. ROGR was designed to give a remote user a method of moving SPOT and caring for the plant. A User Interface (UI) was created to provide a means by which a remote user could interact with the system.

This documentation was written for four main reasons: (1) to detail which components were selected for the system, (2) to provide a rational behind why certain components were selected over alternatives that existed, (3) to provide documentation on how to operate and maintain the system, and (4) to define incomplete work and discuss future improvements that could be made to the system. The document is split into sections for each system component: SPOT (Section 2), ROGR (Section 3), and the UI (Section 4). Additionally, the Appendices provide supporting material on the Bill of Materials (Section A), wiring and structural schematics (Sections B and C), support for component software and the software architecture (Section D.1), other errata (Section E), and future considerations (Section F).

1.1 Project Structure

The X-HAB project was structured as follows:[1,2,3]

Project Advisors

- Nikolaus Correll (Fall)
- Joe Tanner

Project Customers

- Heather Hava
- NASA (Liaisons: Tracy Gill, Gioia Massa, and Morgan Simpson)

Project Team

- Kyle Bruin (Project Leader; Living Systems Team Member)
- Julian Cyrus (Living Systems Team Leader; EPS Team Member)
- Alex Fischer (Systems Engineer; Mechanical Team Member)
- Anitha Ganesha (EPS Team Member; Software Team Member)
- Deepika Gopalakrishnan (EPS Team Member; Software Team Member)
- Matt Gosche (Mechanical Team Leader)

[1] EPS = Electrical and Power Systems
[2] Individuals with a "∗" were volunteers.
[3] Individuals with a "∗∗" were consultants.

- Heather Hava[*/**] (Mechanical Team Member)
- Jordan Holquist[**] (Living Systems Consultant)
- Dane Larsen (EPS Team Member; Software Team Member)
- Bill Liggett[**] (Living Systems Team Member)
- Qi Liu (EPS Team Co-Leader; Software Team Co-Leader)
- Elizabeth "Beth" Luke[*] (Living Systems Team Member)
- Matthew Phillips (EPS Team Co-Leader; Software Team Co-Leader)
- Dharanija Ramaswamy Thatham (EPS Team Member; Software Team Member)
- Himanshi Singhal[*] (Living Systems Team Member) (Fall Semester)
- Poornima Sundararaman (EPS Team Member; Software Team Member)
- Nivedita Swaminathan (EPS Team Member; Software Team Member)
- Manali Torpe (EPS Team Member; Software Team Member)
- Daniel Zukowski[*/**] (Project Leader; Software Team Member)

2 SPOT (Smart Pot)

The Smart Pot (SPOT) functions as a means to self-reliantly grow a plant in a hydroponic setting while also monitoring the plant characteristics (Figs. 1 and 2). One key requirement of SPOT was that it needed to be modular, and have parts that were easily replaceable. This section discusses all aspects of SPOT.[1,2,3]

Figure 1: SPOT (front).

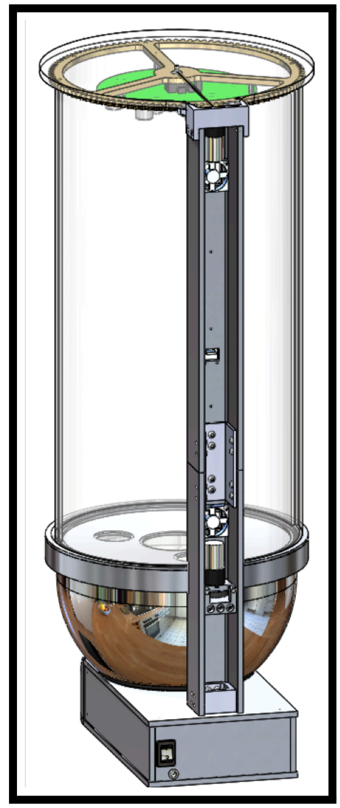


Figure 2: SPOT (back).

2.1 Electrical Components

This section discusses all electrical components of SPOT.

2.1.1 Power Management System

SPOT utilized the Evaluation Module for BQ24617 Multi Cell Synchronous Switch-Mode Charger (Fig. 3) as the power management unit. This module allowed for both testing and final product integration without requiring the creation of a PCB. The charger works by

> [...] automatically restart[ing] the charge cycle if the battery voltage falls below an internal threshold, and enters a low-quiescent current sleep mode when the input voltage falls below the battery voltage. (`www.ti.com`)

[1]The SPOT wiring schematics can be found in Section B.1.
[2]The SPOT software dependencies can be found in Section D.2.
[3]The SPOT mechanical schematics can be found in Section C.1.

The power management board uses the output signal from a 10K OHM NTC Thermistor (Fig. 4) placed inside the sheath of the battery to ensure that the temperature of the battery is in a safe temperature range. SPOT can work while connected to a wart that provides 12 V and 2 A, or can run on an internal battery.

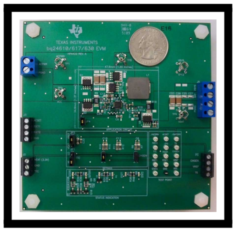


Figure 3: Power management module.

Figure 4: Thermistor resistor.

2.1.2 Microcontroller:

A PCDuino v.2 (Fig. 3) is used to control SPOT. It provides a build in wifi module, a microSD card slot, 24 GPIO ports, 6 ADC ports, an external interrupt pin, TxRx communication, a serial data port, and an ethernet port. The controller uses a Linux Ubuntu 12.04 operating system and runs Robotic Operating System (ROS) Groovy. It was selected due to its cost, built-in features, compatibility with ROS, and ease of use with future upgrades. The PCDuino v.2 requires a 5 V and 2 A power supply.

Through testing, it was found that the 2 GB onboard flash storage was insufficient for the needs of the amount of software that would be implemented on SPOT. To compensate for this, a Kingston 8 GB microSDHC Class 4 Flash Memory Card (Fig. 6) was added to expand the space of the computer to 10 GB.

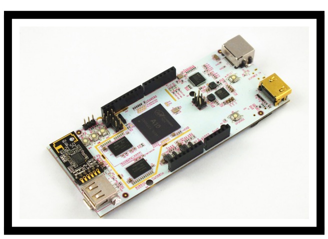


Figure 5: PCDuino v.2.

Figure 6: 8 GB memory card.

2.1.3 Lighting System

Light is one of the most essential elements to sustaining plant life. The SPOT lighting system is comprised of an array of LEDs that supplies the plant with sufficient light within the Photosynthetic Active Region (PAR).[1] 13 Ossram Golden Dragon LEDs (Fig. 7) are used to light the plant. These white light LEDs have a forward current of 350 mA and a forward voltage of 3.2 V. The LEDs are mounted on a custom PCB (Fig. 8) manufactured in-house. This board is attached to the top of SPOT via three screw ports and is able to be lowered when the plant is young by inserting longer standoffs between the top of the board and the ceiling of SPOT. The wires attached to the board are routed through the center opening, up to the ceiling of SPOT and are attached to wires that

[1] PAR denotes the wavelengths of light that the plant is able to use for growth processes.

run down the boom of SPOT. These wires then run down into the electronics box and connect to various power and control outlets.

The final 7" diameter PCB board was designed using Altium Designer. It houses the 13 white LEDs, one red LED, one resistor in series with the red LED, one transistor for the red LED control, as well as inputs for the Vin +/- and red LED control. The other transistor and resistors needed for operation and control of the entire circuit are located on the board found in the electronics box. There is a 0.75" radius hole in the center for wires to enter through. There are three small holes 2" from the center, spaced at 120^{circ} intervals for mounting to the top of SPOT. The concentric circles contain closely spaced LEDs to maximize light focus on the plant. The large amounts of copper act as a heat sink and transfer heat away from the components in a subtle, yet attractive way. A PCB was built to improve the lighting system by making it more appealing visually and better functionally by eliminating the need for extra wires and connections.

The SPOT PCDuino v.2 controls the white LEDs via a TIP120 transistor switch and uses pulse width modulation (PWM) to vary the light intensity. The transistor switch supplies a 12 V power supply to the LEDs 12V DC-DC converter. The red LED produces light with a 656 nm wavelength and can be uniquely controlled[1] as it has its own transistor switch to turn it on. The red LED has a forward current of 400 mA and a forward voltage of 2.15 V. The red LED can be used to help researchers further imitate the plant?s natural environment. It can also be used to change plant behavior. For example, a higher ratio of red to far red light that a plant sees, the shorter the plant will be. This would be beneficial to ensuring the plant does not grow outside the confines of SPOT.

Each white LED has a nominal voltage of 3.3V and a current range of 100mA-1A. Three strings of four white LEDs runin parallel to create a 12 LED circuit, with each LED using 3 V. The red LED runs at 2.15 V, and is in series with a 2 Ω resistor to limit the voltage drop. A BuckPuck 1000 mA Constant Current LED Driver (Fig. 9) limits the current going through the LEDs to 1 A. This LED driver was used because of its ability to handle several strings of LEDs, while providing a constant current appropriate for SPOT's setup. The constant current buck feature makes this attractive from a safety and predictable results standpoint as well. It is in a convenient box that has well marked inputs/outputs. The light from the LEDs are focused using 13° focusing lenses (Fig. 10) and 22° focusing lenses (Fig. 11). They are specially made for the Golden Dragon LEDs used and are comprised of two unified pieces, the lens and body. Despite the datasheet ratings, both of these lenses (and others) exhibited a larger beam than their ratings and it was therefore difficult to plan an optimal lighting layout that focused the light to get the necessary PAR values.

Figure 7: Ossram Golden Dragon LED.

Figure 8: Printed PCB for LEDs.

2.1.4 LCD Display and Buttons

A four line, 20 character LCD display (Fig. 12) was selected for user interface and user feedback. The display was selected due to the number of lines it afforded, its size, and the ease of communication.

[1]The red LED can only turn on when the white LEDs are on.

Figure 9: LED driver.

Figure 10: High-focus lens.

Figure 11: Low-focus lens.

The display utilized a serial interface module (Fig. 13) to communicate with the PCDuino v.2. The LCD display uses the Hitachi HD44780 and PCF8547 protocol for serial I_2C communication. Three waterproof push buttons (Figs. 14 and 15) gave users an interface with the LCD screen menu options. Button Quick-Connect connectors (Fig. 16) were used to easily connect the buttons to the PCDuino v.2. The integrated setup is show in Fig. 17.[1]

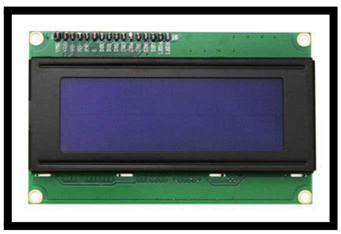


Figure 12: LCD Display.

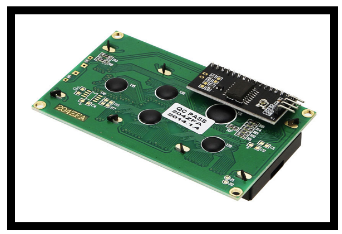


Figure 13: Serial interface module.

Figure 14: Center button.

Figure 15: Left/right button.

Figure 16: Button connectors.

Figure 17: Complete setup.

2.1.5 SPOT Door

The SPOT door is controlled using a 12 V Precision DC Gear Motor (Fig. 18) and a Chopper Stabilized Omnipolar Hall-Effect Switch (Fig. 20). The motor is controlled with a motor driver (Fig. 19), which translates digital signals into clockwise and counter clockwise motor rotations. This motor driver is shared with the motor that rotates SPOT, as is discussed in Section 2.1.6. Two magnets (Fig 21) mounted on the large gear of SPOT were detectable with the Hall-Effect Switch to signal that the door was nearly open or nearly closed. Using the neodymium magnet, the Hall-Effect Sensor output a digital LOW when the magnet came within 0.4375” of the sensor, and a digital HIGH otherwise.

[1]See Appendix D.3 for additional information.

Figure 18: DC motor.

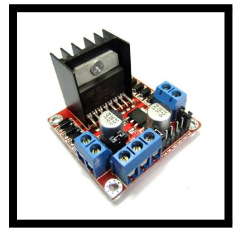


Figure 19: Motor driver.

Figure 20: Hall effect sensor.

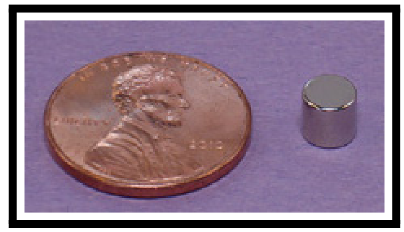


Figure 21: Neodymium Magnet.

2.1.6 Plant Rotation

SPOT is equipped to rotate a plant 360° using a plant rotation motor. This allows a user or ROGR to access the plant at any desired angle, regardless of the limitations that the SPOT door imposes. SPOT's design prevents root damage from occurring during this rotation. The rotation is implemented using a 12 V Precision DC Gear Motor (Fig. 18). The motor is controlled with a motor driver (Fig. 19), which translates digital signals into clockwise and counter clockwise motor rotations. This motor driver is shared with the motor that turns the SPOT door, as is discussed in Section 2.1.5.

2.1.7 Pump System

The plant in SPOT received nutrient liquid via a 12 V Self-Priming Pump (Fig. 22). The pump was selected mainly due to it's reliability, size, and cost. The pump interfaced with food-grade, 1/8" OD silicone tubing (Fig. 23).

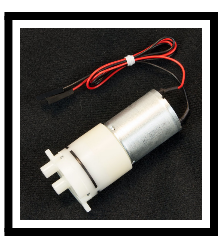


Figure 22: Self-priming pump.

Figure 23: Silicone tubing.

2.1.8 Electrical Conductivity (EC) and Water Temperature Sensors

The electrical conductivity (EC) sensor is used to measure the electrical conductivity of the nutrient solution used for the plant growth. The SP-1-PSC: TDS/EC Sensor Probe (Fig. 24) used also had a built-in temperature sensor to measure the water temperature. EC measurements show the ability of a solution to conduct electricity. The more ions that are present, the higher the electrical conductivity reading. Constant monitoring of the EC value of nutrient solution is needed to retain a balanced ion solution for the plants. If the EC value was lower than the expected value, the ion level of the solution suggested that additional nutrient solution was needed.

Reading from the EC sensor required an analog signal. This was mimicked by sending a digital HIGH, then and digital LOW with a 50/50 duty cycle. This was repeated for three times, and an EC reading was taken on each digital HIGH. The average of these readings was submitted as the final EC reading.

The EC sensor was highly susceptible to noise. Due to this reason, the non-shielded wire entering into the ADC ports was minimized so as to reduce noise as much as possible.

Figure 24: EC sensor.

2.1.9 pH Sensor

The pH sensor measures the pH of the nutrient water in SPOT. Since the voltage obtained from the pH electrode was too small to be measured via an analog port on the PCDuino v.2, a pH amplifying circuit was used. The circuit communicated with the PCduino v.2 via the RxTx serial port. The electrode connected to the circuit via a BNC probe connector. Calibration of the circuit was performed using pH 4.0, 7.0, and 10.0 calibration solution.[1]

Figure 25: pH Probe.

Figure 26: Amplifying circuit.

Figure 27: Calibration solutions.

2.1.10 Humidity and Air Temperature Sensors

The SHT15 (Fig. 28) is a digital humidity and temperature sensor that outputs a fully calibrated humidity and temperature reading. The humidity reading is the relative humidity relative to temperature. It uses a two wire connection for communication that can connect to any two digital pins. The SHT15 sensor was selected over the DHT22 sensor. The readings from the DHT22 sensor, which used a one wire bus protocol, were found to be unstable and dependent on the length of the wire used to interface with the sensor.[2]

[1] See Appendix D.5 for additional information.
[2] See Appendix D.4 for additional information.

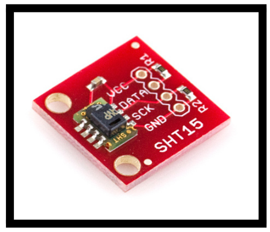


Figure 28: SHT15 digital humidity and temperature sensor.

2.1.11 Camera

To remotely view the plant, VGA camera was used. The camera was selected because it was inexpensive, small in size, lightweight, easy to interface with the PCDuino v.2 via the USB port, and had UVC software support. The field of view of the camera was experimentally measured to be 34°. As the memory card of the PCDuino v.2 was 8 Gb, this was more than enough space to store a daily image of the plant.[1]

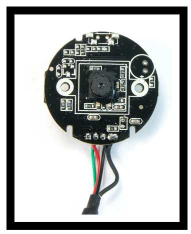


Figure 29: VGA camera.

2.1.12 Liquid Level Detector

A liquid level detector was designed using gold plated 1/8" Stereo Male Audio Cable plugs (Fig. 71). Due to time constraints, the liquid level detector was left incomplete and requires additional work. The idea was to have four plugs protrude from a steel pole at set increments, and use a voltage divider circuit via an analog port to detect varying levels of connectivity that the liquid would provide when it touched both a lower plug and a higher plug.[2,3]

Figure 30: Stereo Cable plugs.

[1] See Appendix D.6 for additional information.

[2] This component has not been finalized yet. While the circuitry has been tested, the circuit and mechanical structure have not yet been combined.

[3] See Appendix E.4 for additional information.

2.1.13 Power Switch

A power switch (Fig. 31) is integrated into the back of SPOT for complete power down. The dual-pole single-throw (DPST) switch turns off power entering into SPOT from the wall wart, and halts power going from the battery to the PCDuino v.2 and all components.

Figure 31: DPST switch.

2.1.14 Ethernet Port

The ethernet port from the PCDuino v.2 needed to be accessible so that a wired SPOT could transmit data upon request. To ensure the electronics compartment remained dry, a waterproof ethernet port (Fig. 32) and ethernet cap (Fig. 33) was selected for this interface. A retractable CAT5e ethernet cord (Fig. 34) was selected to reach from the PCDuino v.2 to the mounted ethernet port.

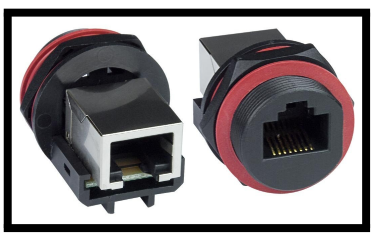


Figure 32: Ethernet port.

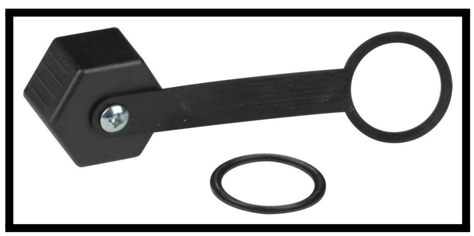


Figure 33: Ethernet port cap.

Figure 34: Retractable cord.

2.1.15 Battery

The SPOT battery provided power to SPOT when it was not connect to a power supply. The Lithium ion (Li-ion) Battery Pack (Fig. 35) was selected due to its high voltage output of 18 V (21 V charging voltage) and its high 8700 mAh capacity. Furthermore, the Li-ion battery was deemed to be made out of acceptable materials by the clients.

Figure 35: 18 V, 8700 mAh battery.

2.1.16 DC-DC Converters

Two LM2596 Buck DC-DC Adjustable Step Down Power Supply Module Converters (Fig. 36) were used in SPOT to provide a 12 V and a 5 V power supply. Aside from their small footprint, the DC-DC converters were selected because they could down-regulate an input 4-35 VDC to 1.23-30 VDC (3 A maximum) using a built-in potentiometer with a maximum 92% efficiency.[1]

Figure 36: DC-DC converter.

2.1.17 Power Jack and Plug

A Sealed Power Jack (Fig. 37) and Sealed Power Plug (Fig. 38) were used for power input into SPOT. The power jack is through mounted to the back of SPOT and allows for the wall wart to plug into the jack. This power plug is located on the wall wart cord.

Figure 37: Power jack.

Figure 38: Power plug.

2.1.18 Plant and Electronics Fans

SPOT has three thermal management fans (Fig. 39). Two fans are used to control and regulate the humidity of SPOT and are located in the boom of SPOT. Based upon the plant?s need for humidity, gas exchange, and temperature, the humidity fans will turn faster or slower, with the ability to pull new air in and old air out of the hood of the plant area.

A third fan is located in the electronics compartment. This fan regulates the temperature and reduces the heat produced by the PCDuino v.2, the DC-DC converters, and the Li-ion battery to normal operating temperatures. This overheating regulation is especially important as most of the electronics are sealed to prevent water damage.

2.1.19 Wiring Module

Due to the limited time, a PCB was not designed for SPOT. Rather, a prototyping perferated board with 2200 through-hole Solder pads was cut to fit on top of the PCDuino v.2 (Fig. 40). Two

[1]To prevent fatal damage to the DC-DC converters, one must ensure that all of the “IN” “IN+” “OUT,” and “OUT+” wires are connected correctly. Connecting them backwords may result in permanent device failure and could also damage other components.

Figure 39: Humidity control and electronics temperature regulation fan.

rows of straight male-male header pins (Fig. 41) were soldered on to the perf board to fit into the female ports of the PCDuino v.2. Additional male-female header pins (Fig. 42) were used to interface with some of the male header pins on the PCDuino v.2. The majority of the circuitry shown in Appendix B.1 was placed on the board. Aside from 22 G wire, the following additional electrical components were used:

- TIP-120 transistors (Fig. 44)
- Resistors of varying values (Fig. 45)
- 1N4007 diodes (Fig. 46)

Right-angled male-male header pins were used as the connector points for each SPOT component. Aside from the pH sensor and the EC sensor, which required limited connection distance between their respective PCDuino v.2 ports to prevent noise, female-female jumper cables (Fig. 47) were used to connect to each sensor.

The wiring module is shown in Fig. 48 and is labeled in Appendix B.1.1.

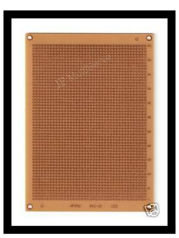


Figure 40: Perf board.

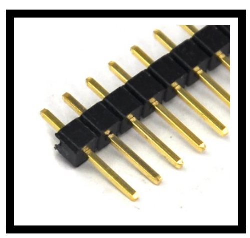


Figure 41: M-M header pins (straight).

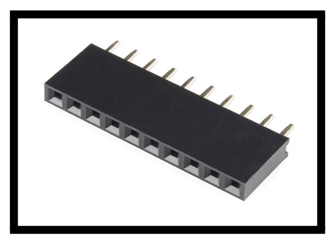


Figure 42: M-F header pins.

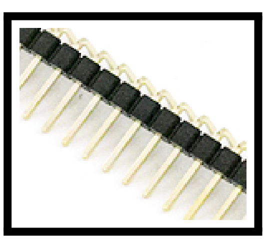


Figure 43: M-M header pins (angled).

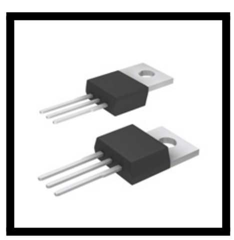


Figure 44: TIP-120 transistor.

Figure 45: Resistor kit.

Figure 46: 1N4007 diode.

Figure 47: F-F jumper cables.

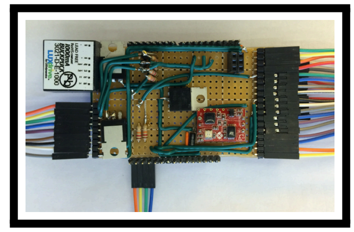


Figure 48: Wiring module.

2.2 Operation

2.2.1 Launching SPOT

To launch SPOT, simply flip the power switch on SPOT to the ON position. All of SPOT's software will start automatically.

2.2.2 Troubleshooting SPOT

SPOT, due to its lack of a screen, is a bit more difficult to troubleshoot. There are two possible methods for accessing SPOT: `ssh`, and a direct connection via a monitor and USB keyboard.

To `ssh` into SPOT, connect to the WiFi network that SPOT is on, and find the SPOT's IP address using the WiFi router's IP address, or from **http://pcduino-ips.larsendt.com/**.

To connect to SPOT with a monitor and keyboard, disassemble the base of SPOT and remove the primary circuit board from the PCDuino. Once the PCDuino is removed, connect it to a wall using a micro-USB phone charger that supplies 5 VDC and 2-2.4 A. Connect an HDMI-capable monitor and a USB keyboard to the appropriate ports on the PCDuino v.2. After approximately 1-2 minutes, the PCDuino v.2 will be fully booted and will display a login prompt. The username and password are both 'xhab'.

Like ROGR, SPOT's primary log file is in its home directory and is named `spot.log`. Log files for individual nodes can be found in `xhab-spot/service_files`, in the home directory. The log file names and formats are the same as ROGR, with each ROS node having a `stdout` and `stderr` file. The `stderr` files will contain any error messages generated by the ROS nodes.

2.2.3 Limitations and Future Considerations

- **Conflicting sensors**

  Full EPS system testing revealed that the pH sensor readings are influenced by the liquid level detector and the EC sensor. Additional work might implement a relay switch on the EC and pH sensors to completely cut the flow of electricity to these two components while the pH sensor is reading values. Preliminary testing also suggested that the EC readings were minimally influenced by the pH sensor and the liquid level detector; however additional tests should re-confirm this.

- **Lighting strength**

  Lighting currently can output the required $300\,\mu\text{mol}/(\text{m}^2\,\text{s})$ at a distance of 12.7 cm. An extra standoff is therefore needed to lower the lighting array from the ceiling of SPOT when the plant is juvenile. The white LEDs give a decent spectrum, but they should be 6000 K instead of 6500 K to give a better PAR reading. 6500 K whites were the only LEDs available at the time however. The 13^{circ} lenses should also be placed on all of the LEDs because the larger angles have too much dispersion. While additional LEDs can be added, more power ability may be needed to accommodate this upgrade.

- **SPOT Dock**

  Currently SPOT is recharged by a wall wart plugging into the power jack (Section 2.1.17)in the base. This can be replaced in the future by a power dock, which would allow ROGR to facilitate SPOT recharging, and would allow ROGR to replace SPOT onto a power dock if/when a user moves SPOT to a different location.[1]

2.2.4 Local Interaction (LCD)

The LCD display and three buttons (Figs. 12-17) afford users the ability to directly view current SPOT data and directly control SPOT operation. A third goal was to utilize the LCD screen as a means to relay messages and warnings to the user based on the data from the SPOT components; however time constraints prevented this goal from being fully realized. The button operation is listed in Table 1.[2]

Table 1: Button Functionality

Button Location	**Button LED Color**	**Button Operation**
Left Button	White	UP: This button moves the cursor up.
Middle Button	Blue	ENTER: This button selects the item/line that the cursor is currently positioned at.
Right Button	White	DOWN: This button moves the cursor down.

The LCD menu is as follows:[3]

1. HOME
   - 1.1. SPOT Info
     - 1.1.1. Water Level [Displays Water Level for 3 sec., then sends user back to 1.1 with cursor at 1.1.1]
     - 1.1.2. Battery Level [Displays Battery Level for 3 sec., then sends user back to 1.1 with cursor at 1.1.2]
     - 1.1.3. **Plant Info** [Currently non-existent. Sends user back to 1.1 with cursor at 1.1.3. Possibly should include: Plant ID, Plant Type, Plant Subtype Plant Age, Options to change ID/Type/Subtype/Age.]
     - 1.1.4. EC Reading [Displays EC Level for 3 sec., then sends user back to 1.1 with cursor at 1.1.4]
     - 1.1.5. pH Reading [Displays pH Level for 3 sec., then sends user back to 1.1 with cursor at 1.1.5]
     - 1.1.6. Humidity Level [Displays Humid Level for 3 sec., then sends user back to 1.1 with cursor at 1.1.6]
     - 1.1.7. Water Temp. [Displays Water Temp. for 3 sec., then sends user back to 1.1 with cursor at 1.1.7]

[1]See Appendix E.2 for additional information.
[2]See Appendix D.3 for additional information.
[3]Menu items needing more work shown in **red**.

- 1.1.8. Air Temp. [Displays Air Temp. for 3 sec., then sends user back to 1.1 with cursor at 1.1.8]
- 1.1.9. Go Back [Sends user back to 1. with cursor at 1.1]

1.2. Controls

- 1.2.1. Rotate Plant
  - 1.2.1.1. Rotate 90 deg. CW
  - 1.2.1.2. Rotate 90 deg. CCW
  - 1.2.1.3. Rotate 180 deg.
  - 1.2.1.4. Go Back [Sends user back to 1.2 with cursor at 1.2.1]
- 1.2.2. Open/Close Door
  - 1.2.2.1. Yes
  - 1.2.2.2. No, Go Back [Sends user back to 1.2 with cursor at 1.2.2]
- 1.2.3. Light Settings
  - 1.2.3.1. Vary Brightness
    - Low (30 min.)
    - Low (2 hours)
    - Low (8 hours)
    - Medium (30 min.)
    - Medium (2 hours)
    - Medium (8 hours)
    - High (30 min.)
    - High (2 hours)
    - High (8 hours)
    - Go Back [Sends user back to 1.2.3 with cursor at 1.2.3.1]
  - 1.2.3.2. Turn LED ON/OFF[1]
  - 1.2.3.3. Go Back [Sends user back to 1.2 with cursor at 1.2.3]
- 1.2.4. Take Picture
  - 1.2.4.1. Yes
  - 1.2.4.2. No, Go Back [Sends user back to 1.2 with cursor at 1.2.4]
- 1.2.5. Restart SPOT
  - 1.2.5.1. Yes
  - 1.2.5.2. No, Go Back [Sends user back to 1.2 with cursor at 1.2.5]
- 1.2.6. SHUTDOWN SPOT
  - 1.2.6.1. Yes
  - 1.2.6.2. No, Go Back [Sends user back to 1.2 with cursor at 1.2.6]
- 1.2.7. Calib. Sensors
  - 1.2.7.1. **EC Sensor** [Currently non-existent. States "Currently not available." message, then sends user back to 1.2.7 with cursor at 1.2.7.1. Needs Additional Work.]
  - 1.2.7.2. PH Sensor [States message: "Place pH sensor in 4.0, 7.0, or 10.0 pH calibration soln." for 3 sec., then presents next screen].
    - 4 pH Calib.

[1] Manual operation of white LEDs only.

- 7 pH Calib.
- 10 pH Calib.
- Go Back [Sends user back to 1.2.7. with cursor at 1.2.7.2]

1.2.7.3. Go Back [Sends user back to 1.2. with cursor at 1.2.7]

1.2.8. Go Back [Sends user back to 1. with cursor at 1.2]

1.3. Messages [Currently non-existent. Sends user back to 1. with cursor at 1.3. Needs Additional Work.]

Although some menu items have not been completed, it is important to note that the menu is completely functional, and notifies the user if an incomplete or non-functional item is selected, and returns the user to the most previous screen.

2.2.5 Charging

SPOT charging is taken care of by the Power Management System (Section 2.1.1). The user is required to plug the wall wart into the barrel plug outlet on the back of SPOT. SPOT can be plugged in for as long or as short as time as desired by the user.

2.2.6 Wireless Communication

Both ROGR and SPOT communicate over standard WiFi. ROGR uses the built-in WiFi chip in its laptop, and SPOT uses the WiFi module built into the PCDuino v.2. This allows for a huge amount of flexibility in the design of the systems by providing an easy-to-use communication layer. Since all communication uses TCP, the network devices can be transparently swapped out with other compatible ones. SPOT also has an Ethernet port for locations where WiFi is unavailable (Section 2.1.14). SPOT's WiFi can be disabled, and it can be connected to a router via Ethernet without needing any changes in the software.

The selection of an aluminum box turned out to be somewhat unfortunate. ROGR and SPOT rely on wireless communication to coordinate all activities, and the aluminum containers for both ROGR and SPOT severely hamper that communication. ROGR's laptop is currently able to sustain wireless communication when inside the box, but there is a noticeable latency increase. The best way to fix this problem would be to run a USB WiFi adapter out of the box and mount it where there is little obstruction by the aluminum case and frame of ROGR. Due to a delay in SPOT being built, the SPOT WiFi has not yet been tested with the aluminum case. It is possible that an antenna will need to be soldered onto the PCDuino v.2 Wifi module.

2.2.7 Sensor Readings

See Appendix E.1 for expected readings for the plant. Note that they have not been verified with SPOTs sensors.

2.2.8 Door Control

For low humidity environments it's best to keep the door closed. This will allow the SPOT system to self regulate the humidity by using the fans to circulate outside air into the system. The liquid reservoir and the LEDs increase the humidity in the system by Refer to LCD screen section. Be aware that manually operating the door will affect the plant environment.

2.2.9 Rotating Plant

As is discussed in Section 2.1.6, a means of rotating the plant is implemented in SPOT to provide access to both local users and ROGR. A local user can utilize the LCD and buttons to manually rotate the plant. The LCD menu is provided in Section 2.2.4.

2.2.10 Providing Light

The correct light cycle for a plant is important for sustained plant growth and production. The minimum photoperiod can incorporate 10-16 hours of light, followed by a period of darkness for the rest of the 24 hour cycle. SPOT will supply light for a total of 14 hours before having its dark cycle last for the remaining 10 hours.

2.2.11 Providing Nutrient Water

Nutrient water is the sole source of macro and micronutrients for a plant in a hydroponic system. Therefore the delivery of both water for the plant and essential vitamins and minerals are dependent upon the supply from SPOT?s reservoir. The hydroponic method here has the plant growing in a basket filled with Rockwool, held above the nutrient reservoir. The water in the reservoir is pumped up onto the lid, which drains into the basket containing the plant. This method allows for the proper aeration of the roots, which prevents root rot. This setup however still maintains enough moisture in the Rockwool to prevent the roots from over drying within a few minutes.

2.2.12 Plant Care

The DRoPPS system is supposed to be able to care for a plant from seed, through growth and harvest. The system will be supplied with pre-seeded cartridges that will be placed into SPOT?s growth chamber, eliminating the need for the actual seeding to be carried out by the system. Responsibilities of SPOT include providing adequate lighting, nutrient water, humidity control, gas exchange, visual inspection via the still-shot camera and monitoring of the microclimate via the embedded sensors.

ROGR is assigned with refilling the nutrient reservoir in SPOT, lifting and moving SPOT, as well as plant maintenance tasks. These maintenance tasks include visual inspection of plant via video feed on arm, placement of seed cartridge in SPOT, trimming plant growth to prevent interaction with SPOT door, pruning for plant health, snipping flowers to prevent premature or over fruiting, harvesting of fruit, and finally clearing of all plant debris that it creates through maintenance. However, at this point ROGR?s arm and end effector, the main components used for plant interaction, do not have the fine abilities needed to complete all that it must. The lack of a vertical joint is not debilitating, but does limit the dexterity of the arm. An end effector that can grasp and cut simultaneously has been designed, but not manufactured. Therefore the current setup should have the ability to cut the stems and various items, but will have difficulty in clearing them and harvesting the fruit. However, the cutting system also has two issues. The first is that it is unwieldy and can have difficulty in targeting specific characteristics of the plant. The second is that the cutting itself sometimes fails as well with the old design.

2.3 Safety

With any venture into space, safety is paramount. This is a just a proof of concept and therefore does not have to meet such stringent criteria. There are however, several areas of concern that should be addressed with this project. Safety concerns can be split into electrical, mechanical, and other miscellaneous hazards for both ROGR and SPOT.

2.3.1 Electrical Hazards

Water is stored in the nutrient reservoir and pumped up through tubing onto the lid to drain to the plant. If water leaks at any point along this supply conduit, a potential hazard to electronics is posed. The electronics are housed in water proof electronics box that was machined in-house, which shields the main components from water intrusion. The fans located in the boom and the LEDs are the most expose. The LEDs are inside the plant enclosure and will encounter humidity in the microclimate. This is a source of concern and the PCB and its connections should be sprayed with an appropriate waterproofing substance to reduce risk of failure. When cleaning the system, the user should also be careful not to introduce water to the electronics.

The fact that the main components, including the PCDuino v.2, DC-DC converters, and battery etc., are housed in the sealed electronics box raises risk for overheating. There are two fans placed in cutouts of boom and ducted down to the box in order to cool the electronics. This is a clever solution because it maintains the resistance to water that the electronics need by not cutting into the electronics box. However, over time, external dust could be blown into and block the duct in the boom.

Short circuits or shocks can occur in the event of fraying wires or touching connections. Liquid spillage, addressed in the previous section, can also be a source of shorting. The connections have yet to be made throughout all of SPOT, but will be made accordingly. The battery has a PCB and the power management board has a fuse built in. A few diodes and fuses have also been placed in other locations, such as on the converters, however again more adequate fail-safes are needed.

Component sturdiness is the final electrical issue discussed here that can lead to safety troubles. This is more pertinent to ROGR, however if it happens to SPOT then functionality would be affected.

2.3.2 Mechanical Hazards

There are several mechanical hazards present on SPOT. The first is sharp edges, which occur on some of the machined pieces of metal. SPOT itself is sturdy and resistant to outside forces, however if it does fall or tips over the sheer weight of the system could pose a danger to the subject in its path. The scenarios in which this risk is increased is when SPOT is placed high up, near the edge of something or is subject to significant external forces. While it is being carried by ROGR, the fall hazard should be minimized by carrying SPOT at a low height and carrying it securely with the flange to lift interaction.

2.3.3 Misc./Other

Control over SPOT in the event of malfunction is important and the unit will be able to be turned off by a physical ON/OFF switch and an ON/OFF switch within the GUI.

2.3.4 Hazards to Plant

The potential hazards to the plant include the following:

- Dehydration from lack of water in reservoir or from poor humidity control by door or ventilation system,

- Fungal and/or bacterial growth in roots or foliage caused by standing water in either location,
- Parasite present,
- Insufficient or improper nutrient concentrations in water,
- Burn from the LED lights,
- Lack of light intensity or full spectrum due to lighting, power fault, or failure to recharge,
- Physical damage incurred by the opening or closing of the door,
- Risk of electric shock in event of short,
- Sensor malfunction leading to false readings and some of the above states, and
- Software malfunction leading to some of the above states.

2.4 Maintenance

SPOT is designed to support plant growth, however in order to do so it must be in clean working order. The following are some of the tasks that must be carried out regularly to ensure a healthy plant.

2.4.1 Assembly

Dirt, grime, and other particulate will accumulate over time, therefore the entire system needs to be cleaned and inspected at the end of every plant life cycle. The connections should also be checked to mitigate the chance of electrical problems. The boom should be inspected for accumulation of dust and dirt that could clog the fan duct. It should be cleaned if a blockage is detected. This should be done at least at the end of every plant life cycle.

2.4.2 Nutrient Reservoir and Lid

A lid was implemented on SPOT to create a dark environment to prevent algae from growing. The lid and nutrient reservoir will accumulate plant particles and nutrient solution over time, and will cause a build up of dirt. These should be wiped clean every month. At the end of a plant life cycle, these should be cleaned with a small percentage of disinfecting liquid to kill any fungi, bacteria or biological matter left over.

2.4.3 Sensors and Fluid Delivery System

The sensors must be checked and cleaned for any film that is deposited on them every month. The EC and pH sensors need to be calibrated in the calibration solution once a month. The pH sensor should be replaced annually.

2.5 Replacement

In the event that a component breaks, it should be replaced quickly and by the same model. Sensors in the reservoir must be replaced only once the reservoir is emptied. The connection for the sensor should be copied from the original as well.

3 ROGR (Remotely Operated Gardening Robot)

The Remotely Operated Garden Robot (ROGR) functions as a means by which a remote user can tend, trim, harvest, and reseed plants in each SPOT (Fig. 49). ROGR currently weights 45 kg and each tank has a 5.6 gallon capacity.[1,2]

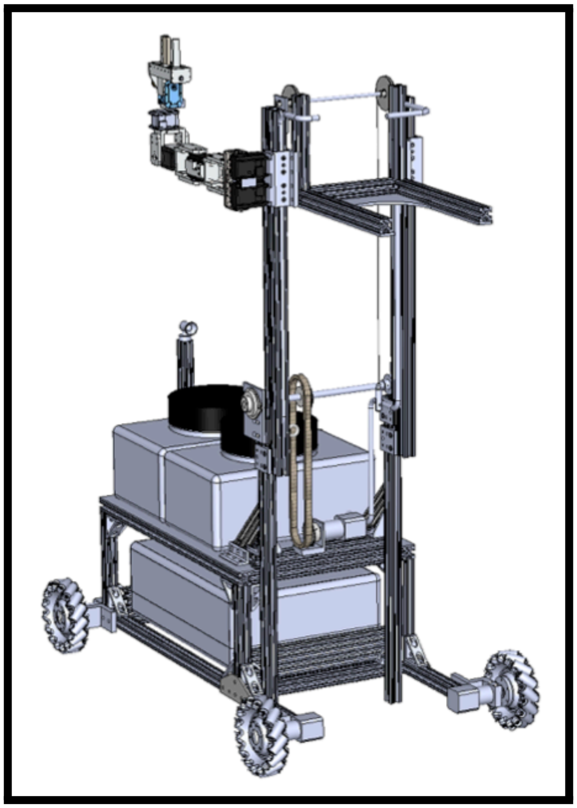


Figure 49: ROGR.

3.1 Electrical Components

This section discusses all electrical components of ROGR.

3.1.1 Power Management System

Like SPOT, ROGR utilized the Evaluation Module for BQ24617 Multi Cell Synchronous Switch-Mode Charger (Fig. 3) with a 10K OHM NTC Thermistor (Fig. 4) as the power management unit. For more information on why this was used, refer to Section 2.1.1.

3.1.2 Laptop

3.1.3 Secondary Controller

A secondary controller was used to interface with the numerous components on ROGR. The secondary controller selected was the SUB20 Multi Interface USB Adapter controller (Fig. 50). It is

[1]The ROGR wiring schematics can be found in Section B.2.
[2]The ROGR mechanical schematics can be found in Section C.2.

a low cost controller with a USB adapter that provides simple interconnect between the ROGR computer and the numerous sensors (pressure sensors, range sensors, battery sensors, water level sensors, water pump, and turret motor). The controller has eight ADC ports, 32 GPIO and PWM ports, RS232, SPI, and I_2C. An Analog/Digital MUX Breakout multiplexer (Fig. 51) was used to further expand the available ADC ports for ROGR using the secondary controller.[1]

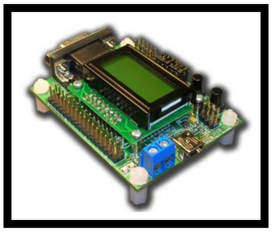


Figure 50: Secondary controller.

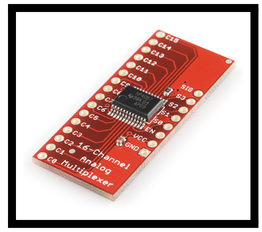


Figure 51: Multiplexer.

3.1.4 Cameras

Three cameras are incorporated on ROGR. A Logitech Webcam C615 (Fig. 52) is mounted on the arm to aid in plant manipulation. It was selected due to its low cost, high definition video stream, tripod mount, light weight, and UVC support for Linux. A Genius 120-degree Ultra Wide Angle Full HD Conference Webcam (Fig. 53) was selected to aid in viewing the plant during plant manipulation. It was selected because it provided a wide angle field of view of 120° and had UVC support for Linux. A Logitech HD Pro Webcam C920, 1080p Widescreen Video Calling and Recording camera (Fig. 54) was selected for the driving camera. It was selected because it came with a tripod mount and was therefore easily mounted on the camera turret, it provided a wide viewing angle, it output a high quality video stream, and it had UVC support for Linux.[2]

To aid in driving, a turret (Fig. 55) was incorporated to rotate the driving camera. The turret allowed the driving camera to rotate 180° along with tilting. The turret was selected due to it low cost, rotation angle, and ease of use. Each servo motor on the turret required only signal, power, and ground wires. The signal lines interfaced with the secondary controller.

Figure 52: Arm camera.

Figure 53: Lift camera.

3.1.5 Wheel Motors

Four NEMA-17 Bipolar Stepper motors with a 26.85:1 Gearbox (Fig. 56) were used for the driving mechanism (one motor per wheel). The motors have a gear ratio of 26.85:1 and produced a torque of 30 kg·cm. These motors were chosen because they had a high enough torque to move ROGR.

[1]See Appendix D.9 for additional information.
[2]See Appendix D.10 for additional information.

Figure 54: Driving camera.

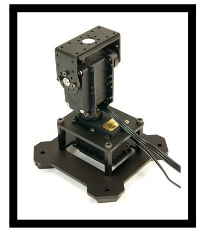


Figure 55: Driving camera turret.

Four NEMA-17 Bipolar Stepper motors with a 5:1 Gearbox and with an 18 kg·cm were also tested. However they failed since they did not have enough torque. Four 1067 Motor Controllers (Fig. 58) were used to interface with the secondary controller and the four stepper motors. WIth the 1067 microcontroller, these motors had a maximum speed of 174 RPM. The specified motor controller was chosen to increase the motor speed.

3.1.6 Lift Motor and Motor Controller

A NEMA-17 Bipolar Planetary Gearbox Stepper motor (Fig. 57) was used for the lifting mechanism. This motor has the gear ratio of 99.5:1 and produced a torque of 48 kg·cm. This was calculated to be enough to lift 1.5× the weight of a full SPOT and lifting arm. This motor was chosen because it had a high enough torque to lift a SPOT. A 1067 Motor Controller (Fig. 58) was used to interface with the secondary controller and the stepper motor. WIth the 1067 microcontroller, this motor had a maximum speed of 44 RPM. The specified motor controller was chosen to increase the motor speed.

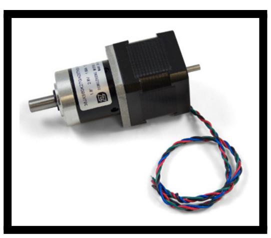


Figure 56: Wheel motor.

Figure 57: Lift motor.

Figure 58: Motor controller.

3.1.7 Electronics Fans

Two Sunson fans (Fig. 59) are located on the case of ROGR. They are used to regulated the temperature in the electronics box and prevent overheating. This overheating regulation is especially important because most of the electronics box is closed to the outside environment to limit potential water damage.

3.1.8 Distance Sensors

Four IR distance sensors are located on ROGR (one on the center of each side). They point out and inform the user about ROGR?s surroundings for collision avoidance feedback. They are attached to the bottom structure of the ROGR chassis. Their range is rated from 10-80 cm. Future work might add additional sensors to give more complete information about the surroundings to the operator. The side distance sensors are more useful in the case of ROGR than for other vehicles because

Figure 59: Sunson fan used on ROGR.

ROGR utilizes mechanum wheels, and can therefore has full planar motion that isn't limited by the direction that it is currently facing.

The Sharp IR distance sensors were selected because they had a decent range, were small, had a simple setup, and were inexpensive. The distance sensor analog output calibration was verified to match that shown in Fig. 61.

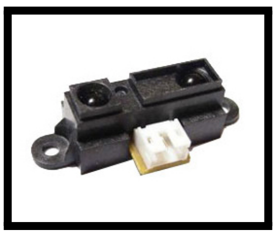


Figure 60: IR distance sensor.

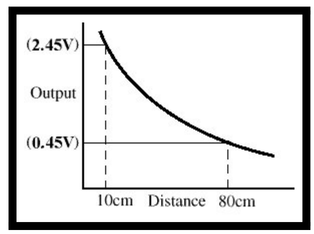


Figure 61: IR distance sensor.

3.1.9 Force Sensors

Two 0.5" Force Sensing Resistors (Fig. 62) are located on ROGR, one on each of the lifting forks. They function as a feedback mechanism to confirm capture of SPOT once ROGR is in position and has begun to raise its lift under the flanges of SPOT. The force sensors gives an analog signal that can be correlated to a mass if calibrated. However they are currently used as a Boolean operator and give a state of on or off. These are not absolutely necessary components, however in the world of limited senses that is remote operation, they afford the user confirmation of an important state of system interaction.

These particular force sense resistors were chosen because they are small, passive, and inexpensive. They were calibrated by pressing the pad while it was on a scale and equating the scale readings to the analog signals being output by the force sensor to the PCDuino v.2. The resistor value in the circuit can be altered, but was chosen because it allowed the analog values to max out at an appropriately selected mass.[1]

3.1.10 DC-DC Converters

Similar to SPOT, the voltage needed to be down regulated for many components on ROGR. One Buck Volt Converter Step Down 12V Car Power Supply Voltage Regulator (Fig. 63) was used to provide a 12 V power supply, and one LM2596 Buck DC-DC Adjustable Step Down Power Supply Module Converters (Fig. 36; *see* Section 2.1.16) was implemented to provide a 5 V power supply for components on ROGR. Aside from the small footprint of the 12 V DC-DC converter, this DC-DC

[1]See Appendix E.5 for additional information.

Figure 62: Force sensors.

converter was selected because it could down-regulate an input 4.5-35 VDC to 0.8-30 VDC (12 A maximum; 100W output maximum) using a built-in potentiometer.[1]

A third DC-DC converter was used to provide power to the ROGR laptop. This was the 150W Boost Converter DC-DC 10-32V to 12-35V Step Up Voltage Charger Module (Fig. 64). It had an output conversion efficiency of 94%.

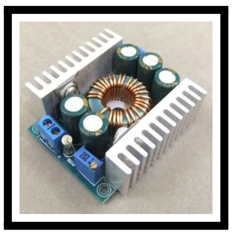


Figure 63: DC-DC converter.

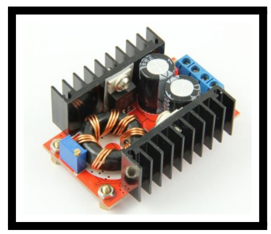


Figure 64: DC-DC converter for the ROGR laptop.

3.1.11 Battery

The ROGR battery provided power to ROGR when it was not connect to a power supply. The High Power Polymer Lithium ion (Li-ion) Battery (Fig. 65) was selected due to its high voltage output of 18.5 V and its high 10 Ah capacity. Furthermore, the Li-ion battery was deemed to be made out of acceptable materials by the clients. The battery is located in a fireproof bag to reduce possible safety hazards that the battery imposes.

Figure 65: 18.5 V, 10 Ah battery.

3.1.12 Arm Mechanism

ARM is used for plant manipulation. It has an end effector for cutting. It has 3 horizontal joints, one wrist. It's mounted on the lift for vertical motion.

[1]To prevent fatal damage to the DC-DC converters, one must ensure that all of the "IN" "IN+" "OUT," and "OUT+" wires are connected correctly. Connecting them backwords may result in permanent device failure and could also damage other components.

3.2 Operation

Launching ROGR is a relatively straight-forward process.

3.2.1 Launching ROGR

ROGR's core computational unit is the laptop inside the metal case. The case can be unlocked and opened in the same orientation that it is mounted in (deep side of the case up). Open the case in that orientation, and the laptop will be easily accessible.

1. Open the case, deep end up
2. Open the laptop's lid
3. Press the laptop's power button
4. When the login screen appears, log in as the user 'xhab', with the password 'xhab'
5. Close the laptop lid
6. Close and replace the case
7. Switch on the power switch on the outside of the case
8. The ROGR software is be running now

3.2.2 Troubleshooting ROGR

ROGR's primary log file can be found in the home directory on ROGR's laptop, under the name `rogr.log`. Initial troubleshooting should start there. Log files for each ROS node can be found in `xhab-rogr/service_files` in the home directory. The log files for the nodes are named by the component that the node corresponds to. There are two files per component: a `stderr` file and a `stdout` file. The `stderr` file is most likely to contain error messages, whereas the `stdout` file will only have non-essential information generated by the node.

When in doubt, restart ROGR's primary process by running the following commands in a terminal:

```
cd ~/xhab-rogr
./launch_rogr.py --kill
./launch_rogr.py --daemon
```

The two `launch_rogr` commands restart any existing ROGR software.

If all else fails, just reboot the laptop, and the software should come back up cleanly.

3.2.3 Limitations and Future Considerations

- **End Effector**

  The 2013-2014 X-Hab project inherited ROGR's arm from the previous year, and along with the arm came all of its problems. Currently, ROGR's end effector is non-functional, which unfortunately limits one of its primary desired capabilities. ROGRs software has the capability to operate the end effector, but there are a couple mechanical issues that prevent it from opening and closing. Ideally we would have liked to do a complete redesign of the effector to allow for both trimming and gripping, but we were severely limited by only having two mechanical engineers.

- **Floor Requirements**

  ROGR's mechanum wheels provide very flexible movement capabilities, but as a consequence are very sensitive to debris on the floor. Currently ROGR has only been tested on a flat linoleum floor, but it is likely it would work well on tile, smooth concrete, and possibly short carpet.

  We discovered that small debris, such as a screw, a pen, or even some thin wire could cause a wheel to skid and interrupt ROGR's movement. Debris 1mm or under in diameter seems to be less of a problem.

  The limitations only really apply to ROGR's rotation and strafing capability. Forward and backward motion should be mostly unhindered by debris and uneven floor surface.

- **Arm Limitations**

  All of ROGR's arm joints are aligned vertical to the floor, meaning that all arm movements are parallel to the plane of the floor. While this is somewhat inflexible, the problem is partially mitigated due to the arm being attached to the lift mechanism. This gives the arm limited vertical motion, and should suffice for most pruning and gripping operations.

  As ROGR's conops indicate, the best location for servicing a SPOT is on the floor, slightly to the front and left of ROGR. This allows ROGR to use all of its capabilities for maneuvering the arm (driving and lifting as well as regular motion).

- **Battery Testing**

  ROGR's charging circuit is damaged, so while it does have a battery that should be able to supply all its needs for a sufficient period of time, operation with the battery is currently not possible, and remains untested. ROGR can be driven directly off of a wall socket with the appropriate power converter (ideally 15V).

- **3D Point Cloud**

  This is one feature that we would have liked to have implemented, but quickly realized that there was not enough time to produce a usable system.

  The 3D point cloud system would use a Kinect-like camera to capture many depth images of a plant from various angles by using SPOT's powered rotation capabilities. The system would be able to reconstruct a 3D point cloud image of the plant to display in the User Interface. Ideally this would allow for much better manipulation of the plant.

- **Range Sensors**

  Currently ROGR only has four range sensors. This gives us a limited picture of ROGR's near environment, but a possible future enhancement would include several more, which would allow us to paint a clear picture of any obstacles within a few meters of ROGR.

- **Turret Motion**

  ROGR's turret camera is located on a structure on the rear of ROGR. The turret chosen is unfortunately only capable of rotating a total of 180 degrees. An obvious upgrade would be to choose a turret that allows for full 360 degree motion without having to worry about tangled cables.

- **Camera Locations**

Camera locations should be tested by users to determine optimal placement. We chose a few obvious locations to place cameras, but it is likely that there are better camera arrangements to better allow a remote user to operate ROGR.

- **Charging Dock for ROGR**

  Currently ROGR must be plugged into a wall for charging, but a possible upgrade would be to create a charging dock, possibly similar to what a Roomba uses. ROGR's power port would most likely be on the rear of the structure, allowing it to back into the dock.

- **Wiring**

  Currently ROGR's wiring is somewhat disarrayed and could use some cleanup. The lesson learned here is to use much longer wire than is initially needed to give some slack and allow for cleaner routing and tying.

- **Fuses**

  ROGR's electronics are somewhat protected from shorts and power surges, but a lot more could be done here to improve reliability. Right now, most of ROGR's electronics are located inside the mostly waterproofed container, but there are several sensors and manipulators that live outside of the box and could be exposed to water or other damage from the environment. Depending on what is damaged, an external short could damage components inside the box. More fuses would probably be the best way to mitigate this risk.

3.2.4 Local Interaction

There is a minimal amount of local interaction necessary for the operation of ROGR. ROGR's primary ON/OFF switch is located on the side of the metal electronics case. When ROGR's power is ON, the green LED above the switch is illuminated. In addition to powering ROGR on via the switch, the laptop must also be manually started. To start the laptop, open the lid, press the power button, wait for the login prompt, log in as the user "xhab" with the password "xhab". After the login process has completed, close the lid of the laptop and store the electronics case back into ROGR.

The other two required local interactions are filling the water and nutrient tanks, and charging ROGR's battery.

To fill ROGR's water and nutrient tanks, unscrew the large black caps and fill the tanks with the appropriate liquids. To charge ROGR, attach a power cable to the outlet in the electronics case, and then plug the cable into a 110 VAC outlet.

3.2.5 Charging

ROGR requires user interaction to be charged. A user should plug in ROGR when it requires additional charge.

3.2.6 Wireless Communication

Please refer to Section 2.2.6.

3.2.7 Sensor Reading

ROGR's primary sensors (aside from the cameras) are the float sensors in its tanks. The float sensors mark a high, a mid, and a low point in both tanks. When the water or nutrient levels have dropped below the low mark, the appropriate tank should be refilled.

3.2.8 Camera Views

ROGR has three cameras: an arm camera, a lift camera, and a rear-facing tail camera (see Section 3.1.4). Without sufficient remote user testing, it is difficult to tell if the current camera setup is usable for remote driving of ROGR. Future work should address whether these cameras should be moved, or whether additional cameras should be added.

3.2.9 Driving Operation

The most effective method of driving ROGR is via the gamepad interface. The gamepad (Fig. 66) is typically used in video games, but due to the nature of ROGR's operation, it provides a clean and intuitive interface for driving, lift, and arm operation.

ROGR's mechanum wheels give it full planar motion that is controllable via the two analog joysticks ("*Left Stick*" and "*Right Stick*" in Fig. 66). The Y axis of the *Left Stick* controls forward and backward motion of ROGR. The joysticks produce an analog output, and therefore they don't need to be fully pushed to the edge of their range to trigger movement. The speed of ROGR can be controlled by how far the stick is pressed. The X axis of the *Left Stick* controls ROGR's side-to-side strafing motion. This is one of two essential functions of the mechanum wheels that would not be possible with other locomotion mechanisms. The X axis of the *Right Stick* controls rotation of ROGR, with "left" on the X axis commanding ROGR to turn left, and "right" on the X axis commanding ROGR to turn right. ROGR comes to a complete stop when both joysticks are released.

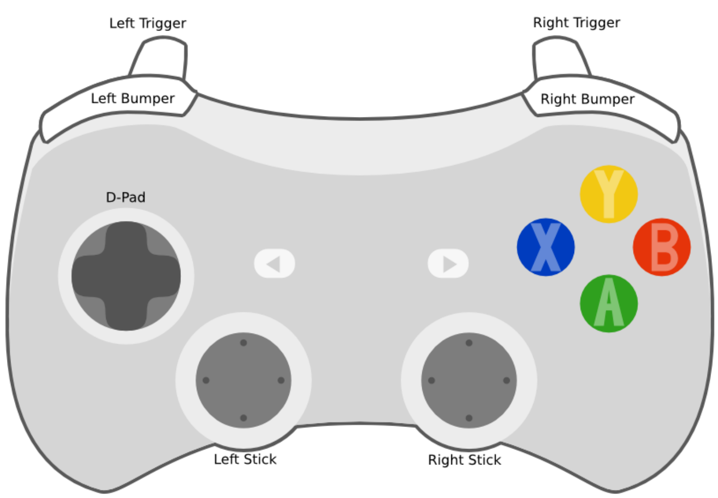


Figure 66: Gamepad diagram.

3.2.10 Lift Operation

The lift mechanism is simple to operate. The *Left Trigger* and *Right Trigger* move the lift up and down, respectively. Like the joysticks, the trigger buttons are analog and can be partially depressed to slow the raising or lowering of the lift. The lift motor comes to a complete stop at the release of both trigger buttons.

3.2.11 Arm Manipulation

ROGR's arm is the most complex to operate, due to the number of joints. To control the arm, six buttons are used (Fig. 66).

- the Left Bumper (LB)
- the Right Bumper (RB)
- the four colored buttons, A, B, X and Y

LB and RB control the opening and closing motion of the joints. LB turns a joint counterclockwise (from above ROGR), and RB turns it clockwise. Which joint is selected depends on which colored button is pressed.

- The 'A' button corresponds to the shoulder (the joint attached directly to the lift).
- The 'X' button corresponds to the first elbow joint that is attached to the shoulder joint.
- The 'Y' button corresponds to the second elbow joint.
- The 'B' button corresponds to the wrist joint, which rotates the end effector.

To control a joint, hold down the corresponding button and then press and hold either LB or RB to articulate that joint in the desired direction. To stop arm motion, simply release all buttons.

3.2.12 End Effector Operation

The end effector is controlled by the Y axis on the *D-Pad* (see Figure 66). Holding 'Up' on the *D-Pad* will close the end effector, and holding 'Down' will open it. To stop opening or closing the end effector, simply release the *D-Pad*.

3.3 Safety

With any venture into space, safety is paramount. This is a just a proof of concept and therefore does not have to meet such stringent criteria. There are however, several areas of concern that should be addressed with this project. Safety concerns can be split into electrical, mechanical, and other miscellaneous hazards for both ROGR and SPOT.

3.3.1 Electrical Hazards

Water is stored in the two tanks and pumped up through the pipes fixed to the lift. If water leaks at any point along this supply conduit, a potential hazard to electronics is posed. The electronics are housed in a nearly water proof brief case housed in the underbelly of ROGR, minimizing the chance of water damage to those components to nearly zero. The most exposed pieces include the motors, cameras, external sensors and exposed wires. These are at risk, but only in the event of an extreme spill.

The fact that the main components, including the laptop, secondary controller, battery etc., are housed in a nearly waterproof enclosure raises the risk for overheating. There are two fans placed in cutouts of the underside of the suitcase in order to cool the electronics. A temperature sensor located onboard the laptop can also be utilized to ensure a safe operating range.

Short circuits or shocks can occur in the event of fraying wires or touching connections. Liquid spillage, addressed in the previous section, can also be a source of shorting. The connections have all been connected well, however a more permanent wiring could make the system more robust. The battery has a PCB and the power management board has a fuse built in. A few diodes and fuses have also been placed in other locations, however again more adequate fail-safes are needed.

Component sturdiness is the final electrical issue discussed here that can lead to safety troubles. If a lift motor, arm motor or range sensor fails for example, the result could be part of the anatomy of ROGR colliding with the plant or user in an undesired manner.

3.3.2 Mechanical Hazards

There are several mechanical hazards present on ROGR. The first is sharp edges, which occur on some of the machined pieces of metal. These should be filed in the future to avoid cuts. There is also a sharp edge located on the end effector that is present to prune the plant. The robotic arm does however have a camera located on it for the operator to gain a first person view of what the end effector is doing.

ROGR itself is sturdy and resistant to outside forces, however if it does fall or tips over the sheer weight of the system could pose a danger to the subject in its path. The scenario in which this risk is increased is when ROGR is loaded with SPOT in an elevated position and an external force is applied. In the event that it tips or falls, ROGR could hurt both itself and something around it.

ROGR is a mobile platform and therefore also poses a hazard by running into objects or humans. It is mounted with three cameras and four range finders to avoid collision, however if these fail or the operator makes an error then damage could be caused. The moving robotic arm and lift are also sources of collision.

3.4 Maintenance

ROGR is designed to support plant growth, by supporting SPOT functions and performing plant care. In order for that to happen, ROGR must be kept in proper working order.

3.4.1 Nutrient and Pure Water Tanks

The nutrient solution tank will accumulate nutrient particles. It and the pure water tank should be inspected for buildup of gunk and algae growth and wiped out every month.

3.4.2 Fluid Delivery System

The pump should be examined if flow rates decrease. The flexible and fixed tubing should also be checked and flushed every month to ensure no buildup of nutrient solution or biological growths.

3.4.3 Lift Motor

The lift motor and pulley system are under stress while carrying SPOT. This system has several moving parts and they must be inspected regularly to ensure they are in proper alignment and nothing interferes with lift motion. The chain must also be kept tight for the motor to pull up the lift without slippage or malfunction occuring.

3.4.4 Wheels

The Mechanum wheels are specialized and give ROGR extra mobility. These wheels can get dirty and trap unwanted items between in the workings of a wheel, stalling it. Therefore they must be cleaned and inspected for such obstructions.

3.4.5 Sensors

The force sensors on ROGR's fork lifts might decalibrate some, but this is OK because they are there just to confirm capture and not measure the actual weight of SPOT. If the range finders start giving faulty readings the problem is most likely a dirty lens, loose connection, or broken part; however they can be recalibrated if need be.

4 User Interface

4.1 SPOT

The SPOT UI page (Fig. 67) shows the summary and status of all SPOTs. For each SPOT, there are buttons to toggle the lights, pump, door, and fan. They also contain an image of the plant. A javascript library called *Cubism* is used to represent the SPOT sensors level. Cubism is used because of the following reasons:

- `Cubism.js` is a plugin for visualizing time series. It is used to construct better realtime dashboards.
- Cubism scales easily to hundreds of metrics and does not require a rescaling adjustment of the vertical axes of data.

The data updates every ten seconds. Despite asynchronous fetching, rendering is synchronized so that charts update simultaneously, further improving performance and readability.

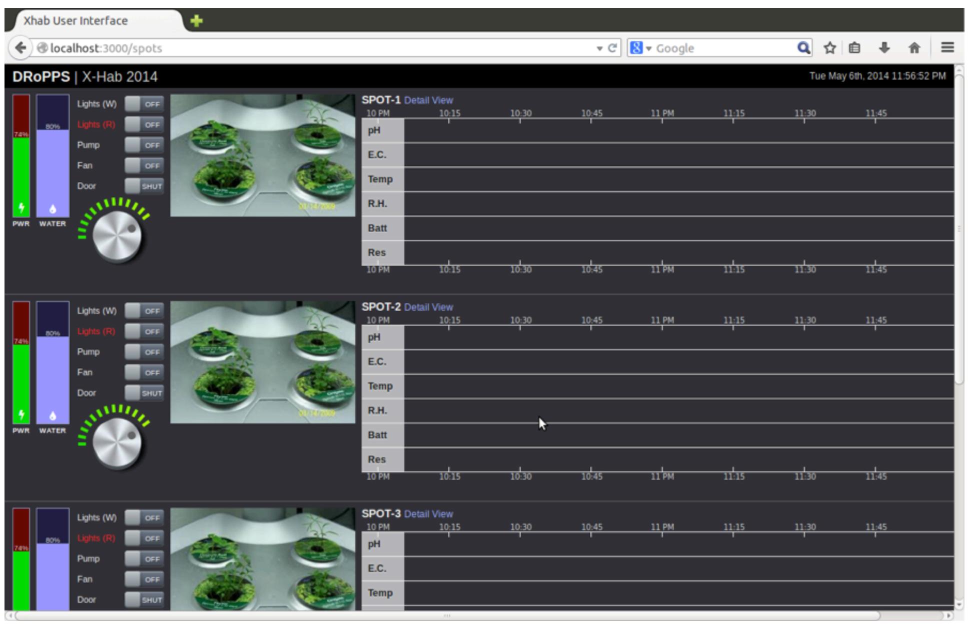


Figure 67: SPOT UI page (screenshot).

4.2 ROGR

The ROGR UI page (Fig. 68) consists of two camera feeds (out of 3) being displayed simultaneously.

The ARM controls are given by shoulder and elbow values and are represented by sliders. The shoulder controls is represented by vertical sliders and the elbow controls is represented by horizontal sliders. This is to distinguish between the up and down movement of the shoulders through 45° to 220° and the sideways movement of the elbow from 60° to 200°. The degree angles were found by varying the ARM angles to find where the servo motors jammed and failed to move further.

The camera turret movement is defined by pan and tilt values. The pan values can be given through a horizontal slider to rotate 360° around the environment. The tilt values are represented by vertical sliders to tilt the turret up and down.

Driving controls are specified using buttons that are aligned as shown in Fig. 68. The various directions for driving are defined by forward, backward, left, right, left-forward, left-backward, right-forward, and right-backward. The lifting mechanism is represented by a vertical slider that can set a desired value and the lift can be carried out by pushing execute lift button. There are toggle buttons to turn on and off the water and nutrient pumps. For now the range finders are represented by buttons to identify each sensor: front, back, left and right, respectively. When the respective button is pressed, it shows the distance at which ROGR is from an obstacle. The two pressure sensors are also represented by buttons to get the respective pressure values which in future will be archived on a database in ROGR to be retrieved and monitored continuously in time using a representation similar to the Cubism javascript.

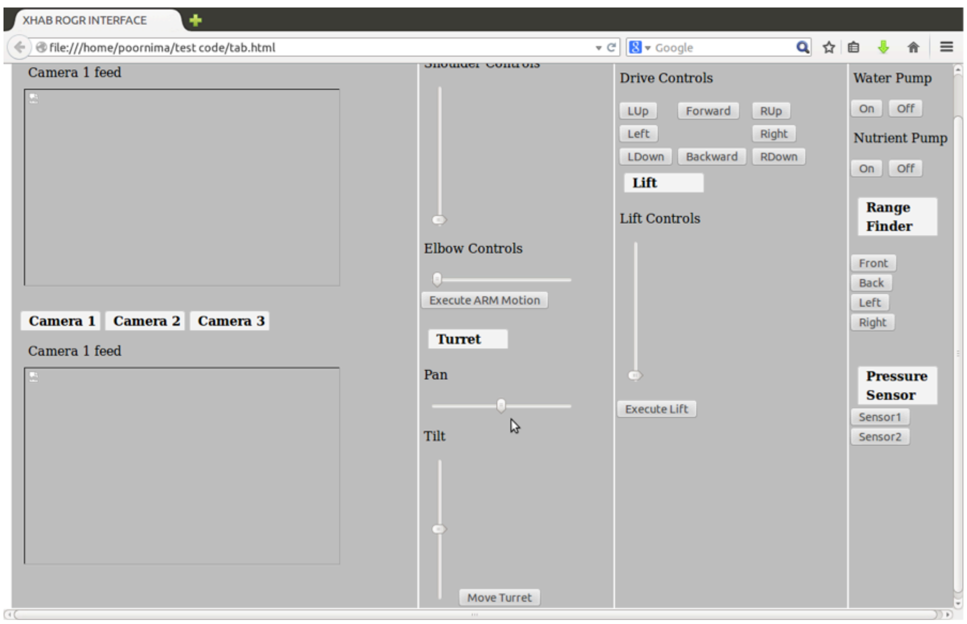


Figure 68: ROGR UI page (screenshot; camera feed not shown).

4.3 Features

The UI currently requires additional work. This is currently being completed during the summer of 2014.

Acknowledgements

The X-HAB team would like to thank NASA for funding this project and for providing a means for individuals to learn and improve their engineering skills in a team-based setting. Furthermore, the team would like to thank Joe Tanner for teaching the Graduate Projects course and acting as a steadfast advisor for the team. Lastly, the team would like to thank Bill Liggett for volunteering his time to help guide the team.

A Bill of Materials

A.1 SPOT

Table 2: SPOT: Bill of Materials - EPS

Item	Quantity	Cost	URL
Evaluation Module for BQ24617 Multi Cell Synchronous Switch-Mode Charger (Fig. 3)	1		
10K OHM NTC Thermistor (Fig. 4)	1		
PCDuino v.2 (Fig. 5)	1		
Kingston 8 GB microSDHC Class 4 Flash Memory Card (Fig. 6)	1		
Ossram Golden Dragon LED - COOL WHITE (Fig. 7)	12		
Ossram Golden Dragon LED - RED (Fig. 7)	1		
Homemade PCB for LEDs (Fig. 8)	1		
BuckPuck - 1000mA Constant Current LED Driver with Dimming (Fig. 9)	1		
LED Lighting Lens (high-focus) (Fig. 10)	6		
LED Lighting Lens (low-focus) (Fig. 11)	7		
LCD Display and Module (Figs. 12 and 13)	1		
Waterproof Push Button - BLUE (Fig. 14)	1		
Waterproof Push Button - WHITE (Fig. 15)	2		
Arcade/Button Quick-Connect Wire Pair (Fig. 16)	2		
Precision DC Gear Motor (Fig. 18)	2		
DROK L298N Dual H-Bridge Motor Driver Module (Fig. 19)	1		
A1126 Omnipolar Hall-Effect Switch (Fig. 20)	1		
Neodymium Disk Magnet - 2/10" OD x 3/16" Height (Fig. 21)	2		
Self-Priming Pump (Fig. 22)	1		
Food Safe Clear Silicone Tubing 3.5mm (10 Meters) (Fig. 23)	1		
HM Digital SP-1-PSC TDS/EC Sensor Probe (Fig. 24)	1		
HI 1001: Flow-thru Monitoring pH Electrode with BNC Connection (Fig. 25)	1		
pH Amplifying Circuit (Fig. 26)	1		
4.0 pH Calibration Solution (Fig. 27)	1		
7.0 pH Calibration Solution (Fig. 27)	1		
10.0 pH Calibration Solution (Fig. 27)	1		
Humidity and Temperature Sensor - SHT15 Breakout (Fig. 28)	1		
Robot VGA Webcam with Mounts (Fig. 29)	1		
DPST Power Switch (JWMW21RA2A) (Fig. 31)	1		
Waterproof CAT5e RJ45 Feed-Thru Coupler, Case Side (Fig. 32)	1		
CAT5e Case Side Waterproof RJ45 Cap with Tether (Fig. 33)	1		
BELKIN A3L791V37RT Retractable CAT5e Networking Cable (Fig. 34)	1		
502-L722AS DC Power Connectors Pwr Jack Sealed (Fig. 37)	1		
502-767KS15 DC Power Connectors Pwr Plug Sealed (Fig. 38)	1		
15x 18650 5S3P 18V 8700mAh Li-ion Battery Pack (Fig. 35)	1		

Item	Quantity	Cost	URL
LM2596 Buck DC-DC Adjustable Step Down Power Supply Module Converter (Fig. 36)	2		
MC35100V2-000U-A99 Sunon Fan (Fig. 39)	3		
Perf Board 6.2” × 4.5” 2200 Solder Pads (Fig. 40)	1		
Gino 5pcs 1x40 Pin 2.54 mm Angle Single Row Pin Header Strip (Fig. 41)	1		
Header - 10-pin Female (PTH, 0.1”) (Fig. 42)	1		
Break Away Male Headers-Right Angle (Fig. 43)	1		
TIP120-ND Transistor (Fig. 44)	5		
Elenco 365 Piece Resistor Kit (Fig. 45)	1		
100PCS 1A 1000V Diode 1N4007 IN4007 DO-41 (Fig. 46)	1		
3 x 40P 20cm Dupont Wire Jumper Cable 2.54 1P-1P Male-Male/Female-Female/Female-Male (Fig. 47)	1		

Additional Notes:

- Due to time constraints, the Liquid Level Detector discussed in Section 2.1.12 and Appendix E.4 was not completed. As a future implementation of the detector may change, the component discussed in Section 2.1.12 was not included in Table 2.

- Heat shrink tubing and 22 gauge wire were not included on this list.

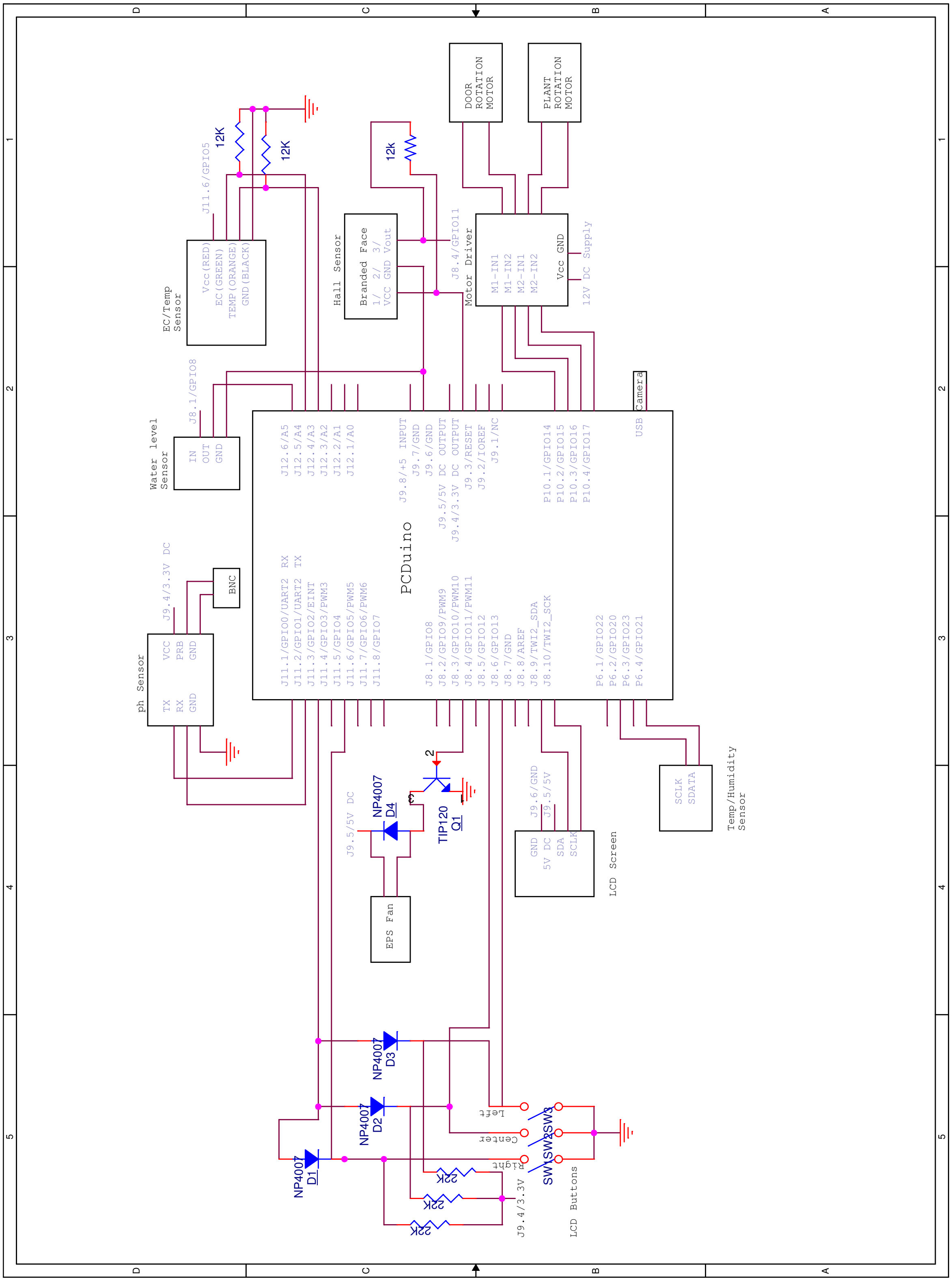
A.2 ROGR

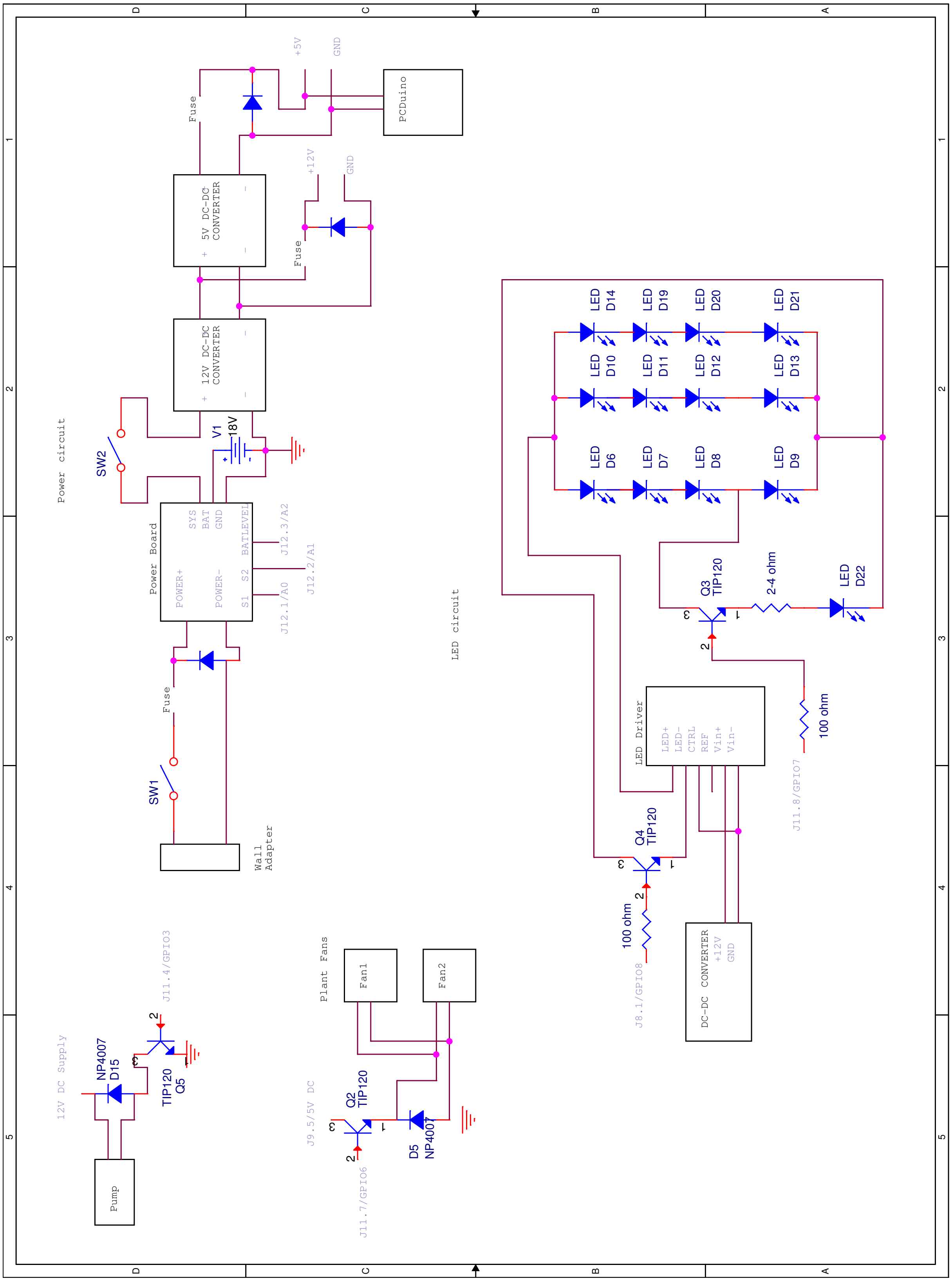
Table 3: ROGR: Bill of Materials - EPS

Item	Quantity	Cost	URL
Evaluation Module for BQ24617 Multi Cell Synchronous Switch-Mode Charger (Fig. 3)	1		
10K OHM NTC Thermistor (Fig. 4)	1		
SUB-20 Multi Interface USB Adapter (Fig. 50)	1		
Analog/Digital MUX Breakout (Fig. 51)	1		
Logitech HD Portable 1080p Webcam C615 (Fig. 52)	1		
Genius 120-degree Ultra Wide Angle Full HD Conference Webcam (Fig. 53)	1		
Logitech HD Pro Webcam C920, 1080p Widescreen Video Calling and Recording (Fig. 54)	1		
Robot Geek Pan and Tilt Kit w/ Servos (Fig. 55)	1		
3327_0 - 42STH38 NEMA-17 Bipolar Stepper with 26.85:1 Gearbox (Fig. 56)	1		
3319_1 - NEMA-17 Bipolar 99.51:1 Planetary Gearbox Stepper (Fig. 57)	1		
ME50101V1-000U-A99 Sunon Fan (Fig. 59)	2		
Sharp IR Distance Sensor - GP2D12 Alternative (Fig. 60)	4		
0.5 Inch Force Sensing Resistor (Fig. 62)	2		
LM2596 Buck DC-DC Adjustable Step Down Power Supply Module Converter (Fig. 36)	1		
DROK 12A/100W 4.5-30V to 0.8-30V DC Buck Volt Converter Step Down 12V Car Power Supply Voltage Regulator (Fig. 63)	1		
150W Boost Converter DC-DC 10-32V to 12-35V Step Up Voltage Charger Module (Fig. 64)	1		
High Power Polymer Li-Ion Battery: 18.5 V 10 Ah (Fig. 65)	1		
Elenco 365 Piece Resistor Kit (Fig. 45)	1		
Elenco 100 Capacitor Component Kit	1		
100PCS 1A 1000V Diode 1N4007 IN4007 DO-41 (Fig. 46)	1		
3 x 40P 20cm Dupont Wire Jumper Cable 2.54 1P-1P Male-Male/Female-Female/Female-Male (Fig. 47)	1		
item	1		
item	1		

B Wiring Schematics

B.1 SPOT




Power circuit
5V DC-DC CONVERTER
12V DC-DC CONVERTER
PCDuino
+5V
GND
+12V
Fuse
SW1
SW2
V1
18V
Power Board
POWER+
POWER-
SYS
BAT
GND
BATLEVEL
S1
S2
J12.1/A0
J12.2/A1
J12.3/A2
Wall Adapter
LED circuit
LED Driver
LED+
LED-
CTRL
REF
Vin+
Vin-
DC-DC CONVERTER
Q3
TIP120
Q4
TIP120
2-4 ohm
100 ohm
J11.8/GPIO7
J8.1/GPIO8
LED
D6
D7
D8
D9
D10
D11
D12
D13
D14
D19
D20
D21
D22
Plant Fans
Fan1
Fan2
J9.5/5V DC
Q2
TIP120
D5
NP4007
J11.7/GPIO6
12V DC Supply
Pump
D15
NP4007
TIP120
Q5
J11.4/GPIO3

B.1.1 SPOT: Wiring

As discussed in Section 2.1.19, the wiring module (Fig. 48) was created in lieu of a PC board due to time constraints. Figs. 69 and 70 and Table 4 describe each connection pin of the wiring module. **Note:** Pins 10b, 10c, and 10d (not shown) were added on June 10th, 2014, and correspond to GPIO11, 3.3 VDC, and GND, respectively.

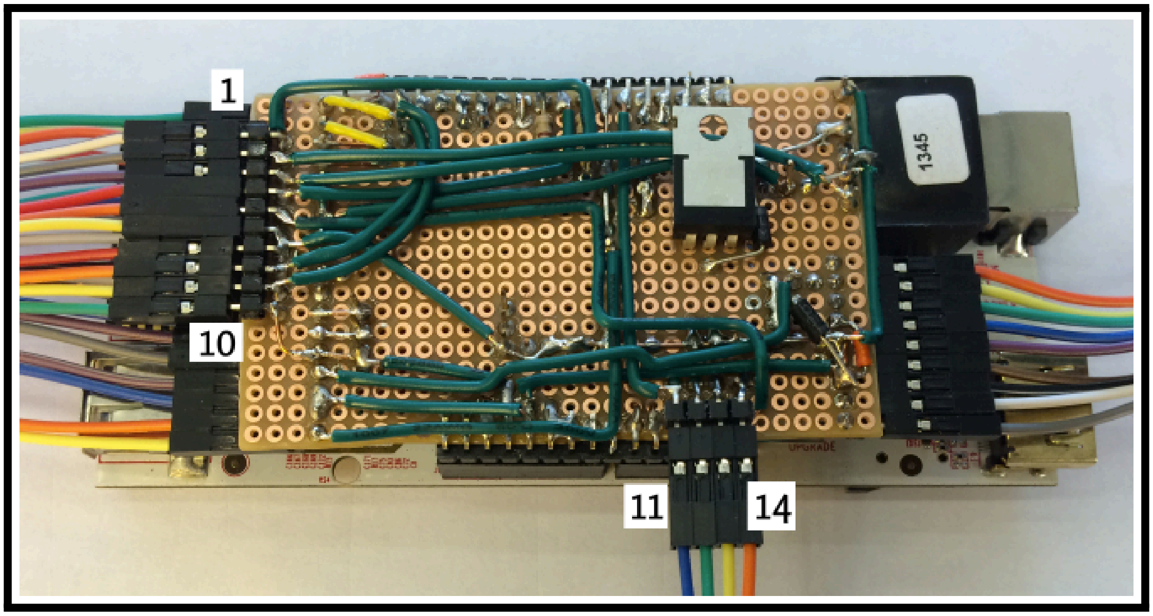


Figure 69: Labeled wiring module (top).

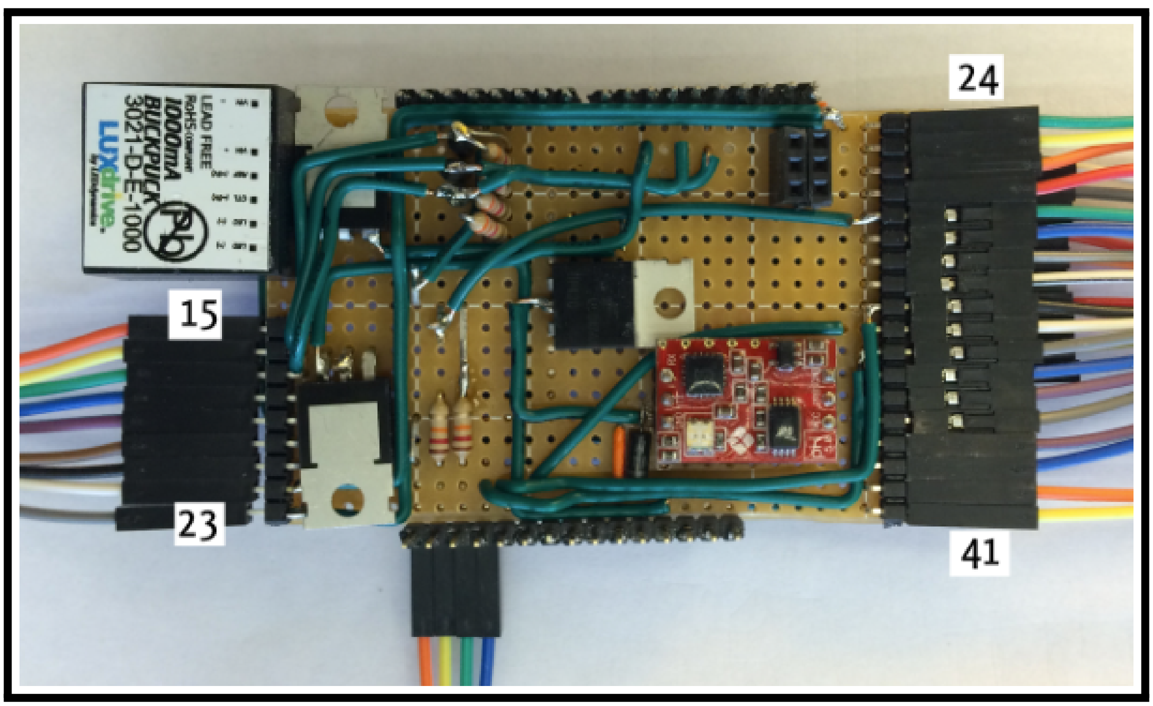
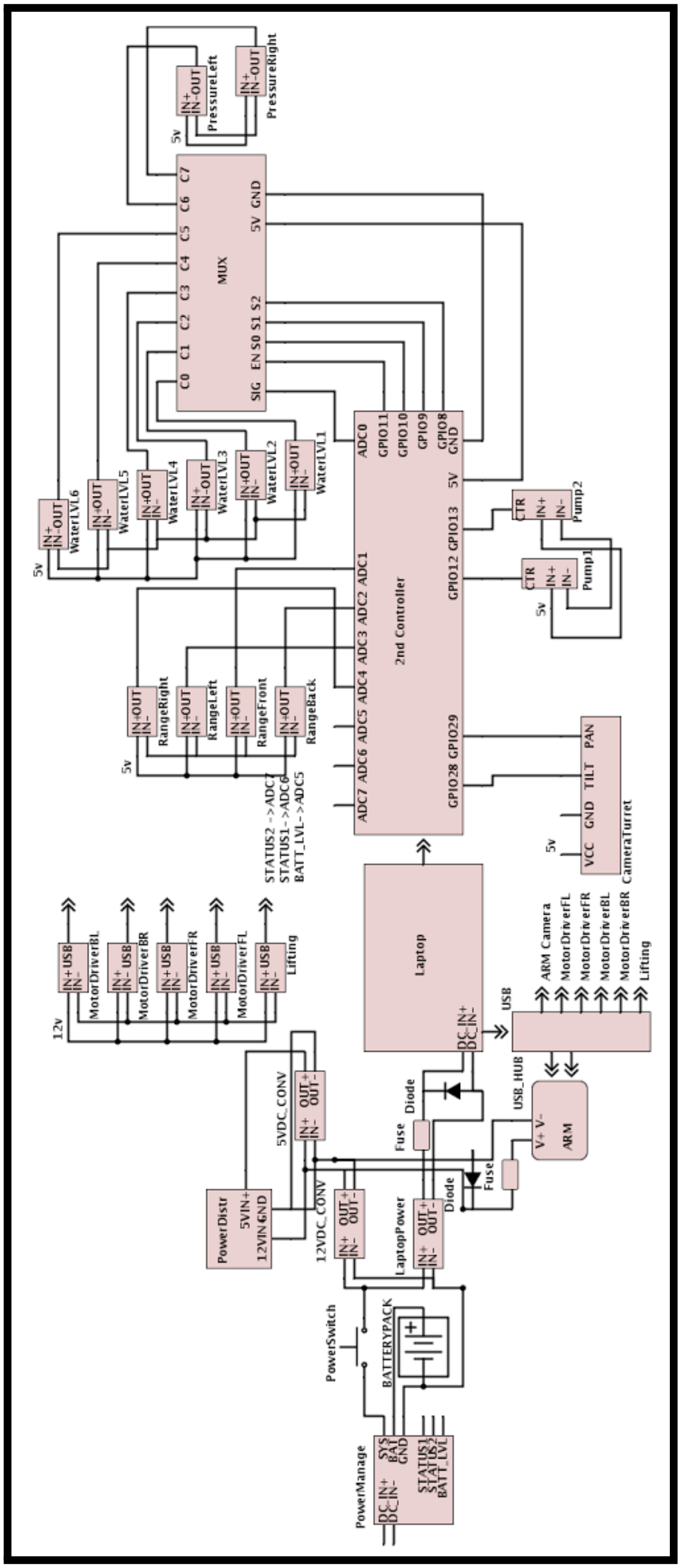


Figure 70: Labeled wiring module (bottom).

Table 4: Labeled Wiring Module

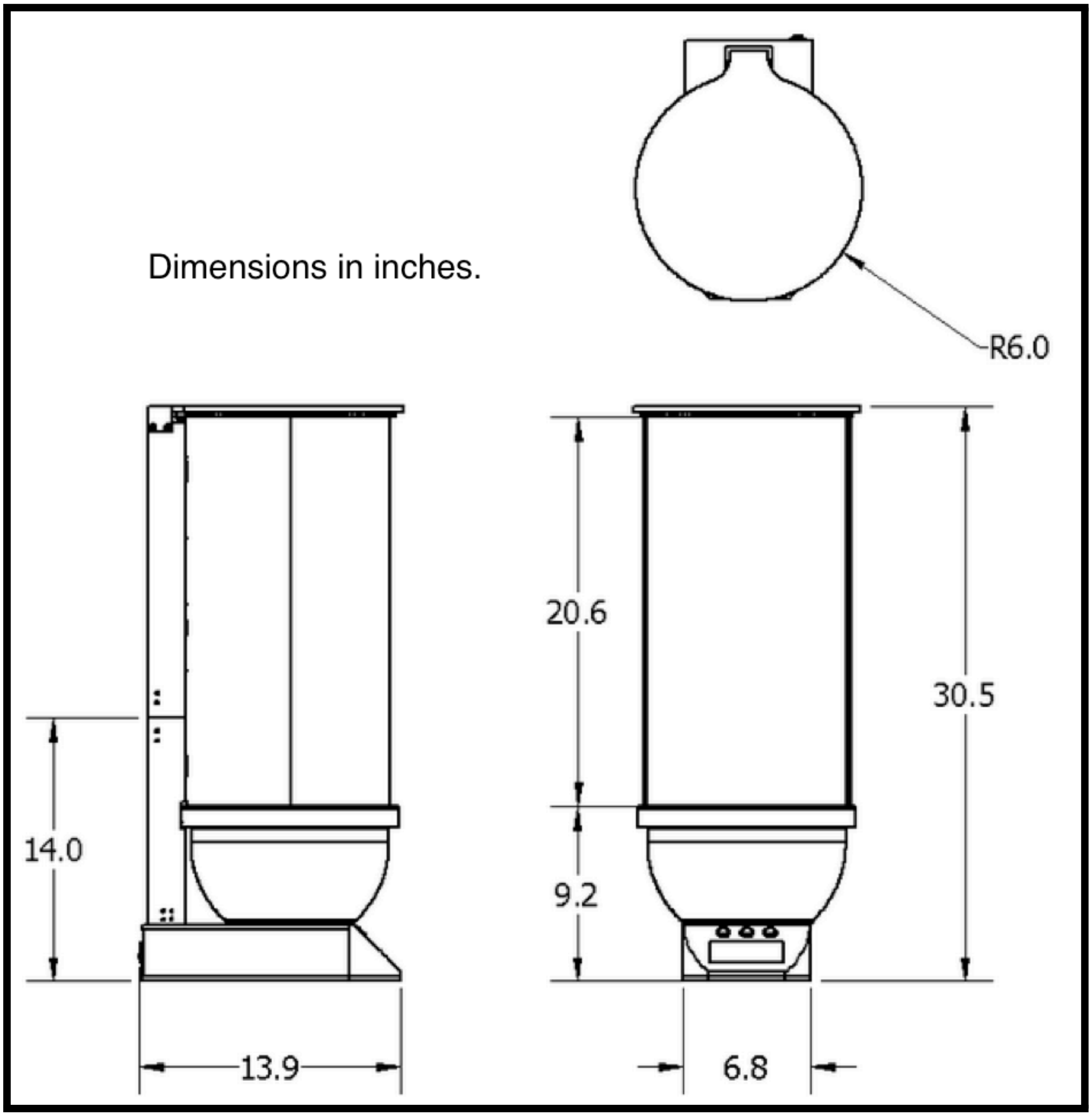
Pin	Pin Description
1	LEDs: LED+ (Red Wire) (Sec. 2.1.3)
2	LEDs: LED- (Black Wire) (Sec. 2.1.3)
3	LEDs: Red LED Control (Controlled with GPIO7) (Sec. 2.1.3)
4	Liquid Level Detector: Digital Output (GPIO8) (Sec. 2.1.12)
5	Liquid Level Detector: Analog Input (ADC5) (Sec. 2.1.12)
6	Liquid Level Detector: GND (Sec. 2.1.12)
7	Humidity and Air Temperature Sensor: GND (Sec. 2.1.10)
8	Humidity and Air Temperature Sensor: SCLK (GPIO20) (Sec. 2.1.10)
9	Humidity and Air Temperature Sensor: SDATA (GPIO21) (Sec. 2.1.10)
10	Humidity and Air Temperature Sensor: VCC (3.3 VDC) (Sec. 2.1.10)
11	EC and Water Temperature Sensor: Digital Output (GPIO5) (Sec. 2.1.8)
12	EC Sensor: Analog Input (ADC4) (Sec. 2.1.8)
13	Water Temperature Sensor: Analog Input (ADC5) (Sec. 2.1.8)
14	EC and Water Temperature Sensor: GND (Sec. 2.1.8)
15	Buttons: Center (GPIO12 and GPIO3/EINT) (Sec. 2.1.4)
16	Buttons: Left (GPIO13 and GPIO3/EINT) (Sec. 2.1.4)
17	Buttons: Right (GPIO5 and GPIO3/EINT) (Sec. 2.1.4)
18	Buttons: VCC (5 VDC) (Sec. 2.1.4)
19	Buttons: GND (Sec. 2.1.4)
20	LCD: GND (Sec. 2.1.4)
21	LCD: VCC (5 VDC) (Sec. 2.1.4)
22	LCD: SDATA (TWI2_SDA) (Sec. 2.1.4)
23	LCD: SCLK (TWI2_SCK) (Sec. 2.1.4)
24	Door: Door Motor OPEN Digital Output (GPIO15) (Sec. 2.1.5)
25	Door: Door Motor CLOSE Digital Output (GPIO14) (Sec. 2.1.5)
26	Plant Rotation: Rotation Motor CW Digital Output (GPIO16) (Sec. 2.1.6)
27	Plant Rotation: Rotation Motor CCW Digital Output (GPIO17) (Sec. 2.1.6)
28	Pump: Pump Black Wire (Sec. 2.1.7)
29	Pump: Pump Red Wire (Controlled with GPIO3) (Sec. 2.1.7)
30	POWER: +12 VDC Input (Sec. 2.1.16)
31	POWER: GND Input (Sec. 2.1.16)
32	Power Management Module: Module Pin S2 (ADC1) (Sec. 2.1.1)
33	Power Management Module: Module Pin S1 (ADC0) (Sec. 2.1.1)
34	Power Management Module: Battery Level Pin (ADC2) (Sec. 2.1.1)
35	pH Sensor: GND (Sec. 2.1.9)
36	pH Sensor: Analog Input (Controlled with Tx and Rx Pins) (Sec. 2.1.9)
37	pH Sensor: VCC (3.3 VDC) (Sec. 2.1.9)
38	EPS Fan: Fan Black Wire (Sec. 2.1.18)
39	EPS Fan: Fan Red Wire (5 VDC) (Controlled with PWM10) (Sec. 2.1.18)
40	Plant Fan: Fan Red Wire (5 VDC) (Controlled with PWM6) (Sec. 2.1.18)
41	Plant Fan: Fan Black Wire (Sec. 2.1.18)

B.2 ROGR

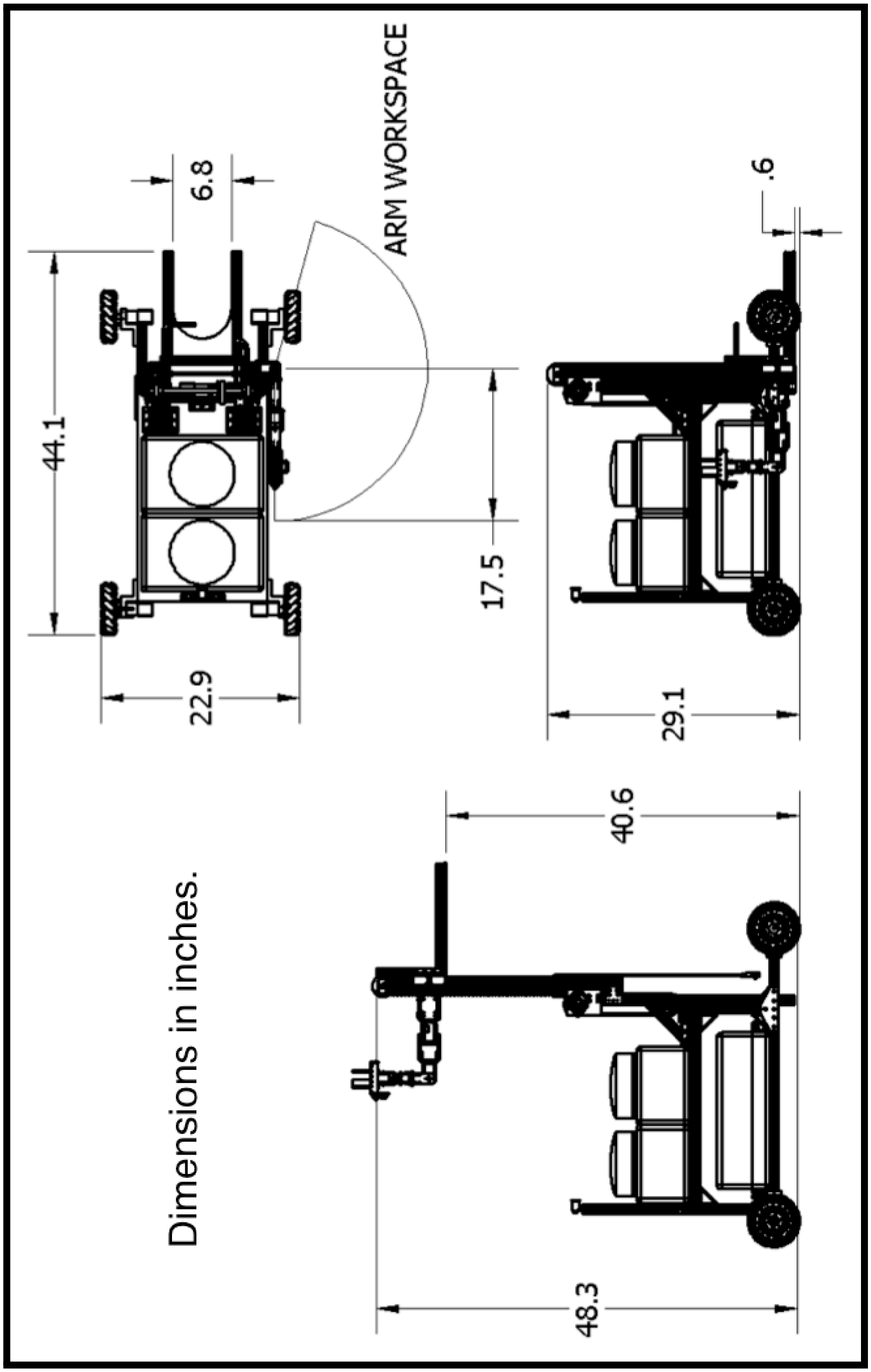

PressureLeft
PressureRight
MUX
C0 C1 C2 C3 C4 C5 C6 C7
SIG EN S0 S1 S2
5V GND
WaterLVL1
WaterLVL2
WaterLVL3
WaterLVL4
WaterLVL5
WaterLVL6
2nd Controller
ADC0 ADC1 ADC2 ADC3 ADC4 ADC5 ADC6 ADC7
GPIO8 GPIO9 GPIO10 GPIO11 GPIO12 GPIO13 GPIO28 GPIO29
Pump1
Pump2
CTR
RangeRight
RangeLeft
RangeFront
RangeBack
STATUS2 ->ADC7
STATUS1 ->ADC6
BATT_LVL ->ADC5
CameraTurret
VCC GND TILT PAN
Laptop
USB
USB_HUB
ARM Camera
MotorDriverFL
MotorDriverFR
MotorDriverBL
MotorDriverBR
Lifting
ARM
12v
5VDC_CONV
12VDC_CONV
PowerDistr
5VIN+ 12VIN GND
LaptopPower
Diode
Fuse
PowerSwitch
BATTERYPACK
PowerManage
SYS BAT GND
STATUS1 STATUS2 BATT_LVL

C Structural Schematics

C.1 SPOT



C.2 ROGR


ARM WORKSPACE
6.8
.6
44.1
17.5
22.9
29.1
40.6
Dimensions in inches.
48.3

D Software Code

D.1 ROS Architecture

We used a service-based architecture for both SPOT and ROGR, which is highly encouraged by the ROS libraries. Each electronic component of the system has an associated "ROS Node" which is responsible for integrating that component with the rest of the system. More information about the specifics of writing a ROS-based software package can be found on the ROS website, ros.org.

The specifics of our system lie around our choice of ROS topics, our message formats, and how we standardize sensor readings.

D.2 SPOT Dependencies

Each of the following applications can be installed using the following command:

D.3 LCD Interrupt Handler

Because handling interrupts requires highly responsive software, we chose to write an interrupt-handler shim in C. It is responsible for directly subscribing to the software interrupts, reading the appropriate pin values, and writing them to a file for the python-based LCD menu application to consume. The external interrupt uses one of the two available external interrupt ports on the PCDuino v.2.

D.4 Humidity and Temperature Sensor (SHT15)

Arduino library used: **(Link)**

All the necessary files can be found here: **(Link)**.

How to port to pcduino:

D.5 pH Probe

D.6 SPOT Camera

Working - Connect the camera to Arduino board via USB.

Note: This information may_be out of date! Dane installed a different camera package, and this information may not longer be relevant.

D.7 ROGR Architecture

Each component has a task message and a common data message.

D.8 ROGR Arm Architecture

D.9 Secondary Controller

The C library can be found in the **download** section here **(Link)**.

D.11 Graphic User Interface User Guide

Software Used:

Installation and Getting Started with Ruby:

Setting up database:

Installing Ruby libraries:

Starting up the rails server:

E Miscellaneous Information

E.1 Plant Sensor Readings

Table 5: Optimal Expected Plant Readings.

	Specifications	**Frequency**	**Comments**
Lighting (intensity)	150 µmol/(m^2 s) min. (300 µmol/(m^2 s) opt.)	14-18 hours (10-16 minimum)	8.65 mol/(m^2 d) or 30 W/(m^2 d)
Lighting (spectrum)	Peak light usage: 425 nm (blue) and 725 nm (red). Low usage: 525nm (green) to 625 (yellow)		Use white light during growth. Then introduce red light for fruiting.
H_2O/Nutrients	1 Gallon	Every 4-7 days	Refilled by ROGR.
Humidity	45-85% (70% optimal)		Regulate with door and fan circulation system.
pH	6.0-6.8 pH		Regulated by nutrient soln. and water from ROGR.
EC	1.8-2.5 mS/cm		10-3000 µS/cm meter range
Air	Circulate air enough to see leaves move for CO_2 intake and to decrease chance of fungal and bacterial growth.	Dependent upon humidity and CO_2 in. environment	Regulate with door and circulation system.
Air [CO_2]	400-1,000 PPM		
H_2O Dissolved O_2 Content (DO)	Optimal: 9 PPM		Water oxygenates naturally when delivered to plant.

(Note: Plant specifications vary slightly depending on crop type.)

E.2 SPOT Power Dock

SPOT currently is outfitted with a power jack in which a wall wart can plug in to for battery resupply and the immediate acquisition of system power. This is a robust and effective method; however a local user will have to assist with this process. In the future a power dock and a corresponding dock capture located on SPOT can be added to allow for the recharging of SPOT to be facilitated by ROGR. ROGR will essentially lift SPOT up and set it down such that SPOT's capture structure fits onto the dock for charging. The dock will be plugged into a wall outlet and could consist of a cone-like shape that has positive and negative conducting rings along its outside surface. SPOT would then have a cone capture, which will be a hollow and slightly larger version of the dock in order to allow it to fit over the top of the cone. The inside of the cone capture will contain two conducting rings that will line up with the rings on dock. When these rings align they will conduct power from the wall wart, to the dock rings, to the capture rings, and finally to the power management system in SPOT. Safeguards to prevent shock to users or inappropriate charging such as contact switches can be implemented as well.

E.3 ROGR Power Dock

ROGR currently is outfitted with a cord to be plugged into a wall outlet for battery resupply and the immediate acquisition of system power. The 120 VAC source is converted at the onboard power supply to a DC voltage that can be handled by the power management system. Although this is a robust and effective method, a local user will is required to assist with this process. In the future, a power dock and a corresponding docking system located on ROGR could be added to allow for recharging to be accomplished by ROGR on its own. The charging station will be plugged into a wall outlet and would consist of parallel tracks for the wheels to help the robot guide align itself over the station. A back wall would be perpendicular to and connect the tracks. The charging dock itself would be a box and sit in the middle of the wall. The box would have two slits in it, running from front to back, for the positive and negative prongs on ROGR. The positive and negative prongs on ROGR would be attached to the charging box on ROGR and would stick down below the undercarriage. This setup would allow ROGR to simply drive up to the station and have its prongs slide into the positive and negative slits as the wheels are guided by the tracks. Aligning help, such as the quintessential line finding technique to guide the robot in a straight line could aid this process. Safeguards to prevent shock to users or inappropriate charging such as contact switches can be implemented as well. One starting point for a ROGR dock might be to look at current remotely operated lawn mowers, as these machines also utilize a two-pronged docking system.

E.4 Liquid Level Detector

As discussed in Section 2.1.12, the liquid level detector requires additional work for it to reach a completed state. The circuit that was designed and tested (and implemented in the software) for measuring the liquid level in SPOT is shown in Fig. 71.

One problem that was discovered with the liquid level detector was that the electrical characteristics of the liquid level detector influenced the readings from the pH sensor (and possibly the EC sensor as well, although this was not tested). A finished liquid level detector should look into possible alternative methods of measuring the water level, or look into using a relay switch to cut off power when the liquid level detector is not being used.

E.5 Force Sensors

The Force Sensor Resistors (FSR) from Section 3.1.9 are wired as follows:

- Red wire: 5V output to sensor
- Black wire: Ground
- White wire: Analog input to sense voltage drop (can also be digital for our application if we run out of analog inputs)

The circuit for measuring the analog output is shown in Fig. 72, where the resistance R can be any desired value. Table 6 shows measured electrical values at different force measurements for $R = 10,000\Omega$.

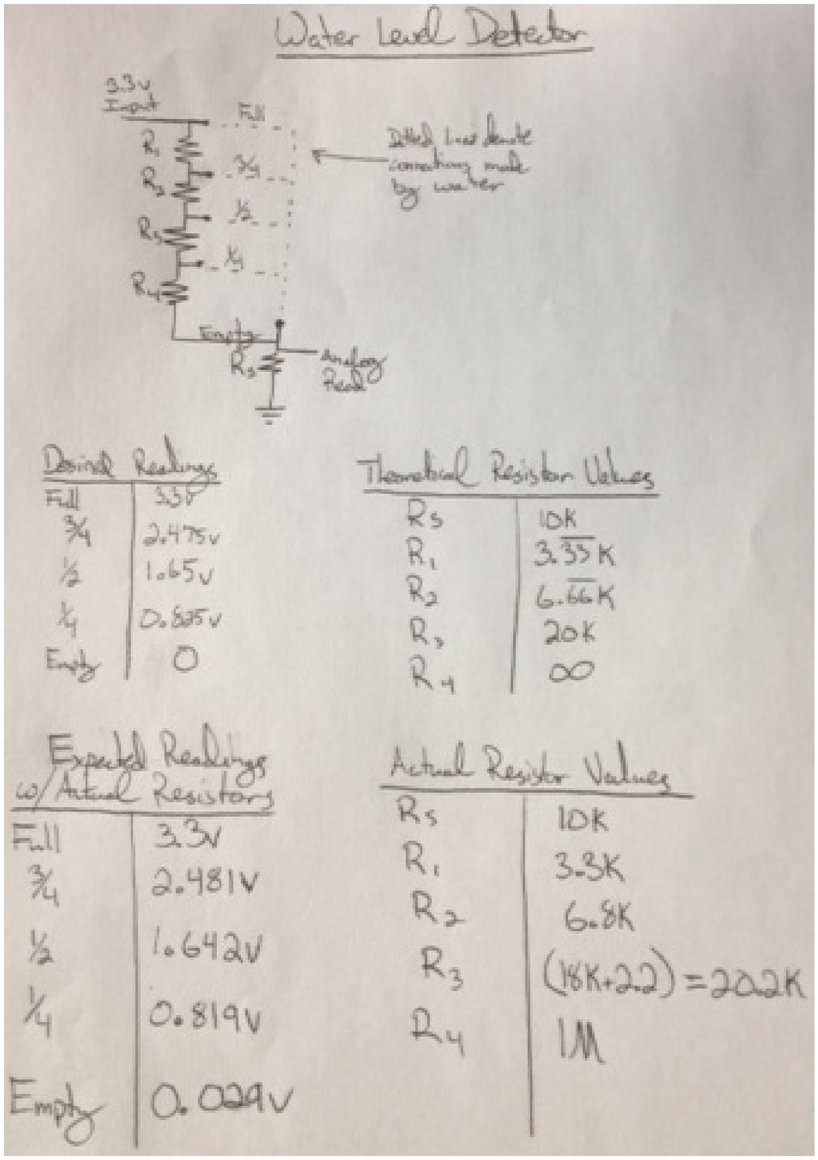


Figure 71: Analog circuit designed to measure the level of liquid in SPOT.

Table 6: Measured Voltages at Different Force Loads on the Pressure Sensor

Force (lb)	Force (N)	FSR Resistance	FSR+R Resistance	Current through FSR+R	Voltage across R
None	None	Infinite	Infinite	0 mA	0 V
0.04 lb	0.2 N	30 KΩ	40 KΩ	0.13 mA	1.3 V
0.22 lb	1 N	6 KΩ	16 KΩ	0.31 mA	3.1 V
2.2 lb	10 N	1 KΩ	11 KΩ	0.45 mA	4.5 V
22 lb	100 N	250 KΩ	10.25 KΩ	0.49 mA	4.9 V

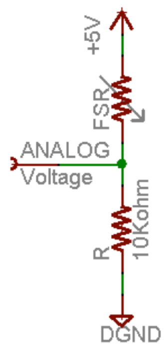


Figure 72: Analog circuit used to measure varying force measurements of the FSR.

F Future Considerations

F.1 LCD Menu

As mentioned in Section 2.2.4, a small portion of the LCD menu still remains to be completed. In particular, the following items are currently incomplete:

- **Plant Info:** Item 1.1.3 would allow a user to see information about the specific plant that is housed in SPOT. This might include Plant ID, Plant Type, Plant Subtype Plant Age, Options to change ID/Type/Subtype/Age.
- **EC Sensor Calibration:** Item 1.2.7.1 would allow a user to re-calibrate the EC sensor, if necessary. Limited experience in using this sensor prevents the team from knowing if such a function would be necessary.
- **Messages:** Item 1.3 would relay messages and warnings to the user based on the data from the SPOT components. Ideally, the 1.3 item "Messages" would change to "Messages (ϕ)", where ϕ would be the number of new messages. Due to limited information/knowledge on plant data, as well as time constraints, this menu item was left incomplete.

Aside from these menu item improvements, future UI adjustments might also grant the user the ability to manually turn on the watering pump, manually transfer data via ethernet upon command, and might turn off the LCD screen backlight when the LCD screen is not in use.