Final Documentation

SCUTTLE Power Management System

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1. Executive Summary

Current iterations of the MXET department’s SCUTTLE robot function on an individual level and must be manually plugged in for charging purposes. In order to further expand the capabilities of the SCUTTLE, we developed a system to wirelessly charge, track, and manage these robots. Our solution allows the SCUTTLE robot to function as part of a fleet rather than as an individual system, demonstrating the capabilities of the Internet of Things. Our solution, the Scuttle Power Management System, utilizes a charging station with wireless charging capabilities, wireless communication, and an RFID interrogator in order to identify the SCUTTLE robots. The system also utilizes an onboard module on the SCUTTLE robot that senses battery level information, provide passive RFID communication, and have the intelligence necessary for wireless communication. The SCUTTLE On Board module and the charging station will both upload sensor data to the Cayenne IoT database and present information to this interface, allowing the user to have a top-down perspective on the status of all of the robots with the onboard module installed. The station is able to accommodate one SCUTTLE robot at a time. Additionally, the SCUTTLE robot has range limited autonomous docking capabilities with the station so as to further automate the charging process.

2. Problem Statement

2.1. Background

The SCUTTLE, or the Sensing Connected Utility Transport Taxi for Level Environments, is used by Texas A&M's MXET department to educate students about robotics, mechanical design, and general electronics. Each SCUTTLE is usually operated by a team of students in the MXET 300 class, or developed on an individual basis as students progress through the program. Additionally, the SCUTTLE is eventually intended to be used in industry, such as for use transporting equipment from location to location.

2.2. Project Problem Statement

Current iterations of the SCUTTLE robot function independently and must be manually plugged in for charging purposes. This prevents the SCUTTLE from being used for any semi-autonomous or autonomous functionalities in industrial settings. Additionally, the robot typically operates on an individual level. In order to be used in a warehouse, factory, or other industry setting, these robots have to be used on a multi-platform basis for expandability purposes. Lastly, the SCUTTLE robot does not currently have many IoT implementations. From an educational perspective, all of these items contribute to an expansion opportunity for the department.

2.3. Solution

In order to further expand the capabilities of the SCUTTLE, we developed a system to wireless charge, track, and manage these robots. The SCUTTLE Power Management System uses a range limited autonomous docking sequence using computer vision and a digital compass to navigate itself to a charging station. This station uses induction charging pads to transfer voltage to any properly equipped SCUTTLE's battery pack without the user having to manually replace its batteries. Additionally, the system brings multiple new IoT functionalities to the SCUTTLE robot. All battery management functions are tracked through the Cayenne IoT database. The site's Graphical User Interface also provides SCUTTLE identification and charging status information to the user.

3. Concept of Operation

3.1. Operational Description and Constraints

This project is specifically designed for the SCUTTLE robot. Therefore, the SCUTTLE On Board module is specially tailored to attach modularly to the SCUTTLE itself. In addition, the charging station is designed to be compatible with power outlets found commonly in buildings throughout the United States. Additionally, our project has been designed to use “off the shelf” products in key areas such as the induction pads on the charging station and the receiver pads on the SCUTTLE. The purpose for this design choice originates through a need for the charging station and SCUTTLE On Board module to be easily maintained by users outside of the project team. Both the charging station and the SCUTTLE use the Beaglebone Blue microcontroller. This allows the system to fit into the MXET 300 coursework easily, as all students, professors, and faculty responsible for developing the curriculum already use the Beaglebone Blue. Lastly, the SCUTTLE robot may be used in a variety of locations, therefore the docking station is designed to be easily transportable to accommodate the flexibility of the SCUTTLE’s operating environment.

3.2. System Description

The three main modules, the Charging Station, SCUTTLE On Board module, and Internet of Things (IoT) Database each provide the following functionalities:

Charging Station

The Charging Station, also referred to as simply the Station, is responsible for providing sufficient power to the internally located BeagleBone Blue as well as three wireless charging base pads. Mechanically, the Station also holds the target which the SCUTTLE uses to locate its position as well as guard barriers to help align the SCUTTLE while docking. Additionally, the Station provides RFID identification of a docked SCUTTLE, and reports this information wirelessly to an IoT database using the internal BeagleBone Blue. As a supporting feature, the Station also wirelessly publishes its heading on a 360 degree coordinate plane to assist with the SCUTTLE’s docking procedures.

SCUTTLE On Board Module

The SCUTTLE On Board module, abbreviated as the S.O.B., includes not only mechanical modifications, but also software additions to the existing SCUTTLE platform. The mechanical additions include three wireless charging receiver pads mounted on the front rail which provide charging power to SCUTTLE's batteries, as well as a passive RFID identification card also secured to the front rail for communicating to the Station. Lastly, a Printed Circuit Board, or PCB, is attached to the inside of the front rail and connects SCUTTLE’s BeagleBone, battery pack, and receiver pads for charging regulation and monitoring.

The software additions include supporting code for docking SCUTTLE autonomously at the charging station using the onboard webcam and compass, as well as code for battery charge monitoring and communication to an IoT database.

Internet of Things Database

The final module for the project, the Internet of Things Database, or IoT Database, is responsible for storing information regarding the Station's occupancy status as well as SCUTTLE's battery voltage levels. Additionally, the Database also graphically represents this information in a user-friendly manner. For the purposes of our project, we chose Cayenne to store and display this data.

Figure 1.0: SCUTTLE Power Management System Conceptual Block Diagram

3.3. Modes of Operation

Both the SCUTTLE and the Charging Station have three possible modes of operation. Their respective descriptions are listed below*:

Charging Station:

1. Unpowered: The Station is not plugged in to an appropriate power source. In this mode, no backup power is provided for the Station's internals. The Station can not communicate any information or provide charging power to the SCUTTLE in this mode.
2. Power, Not Charging: The Station is properly connected to an appropriate power source, yet no SCUTTLE is present to receive charging power. In this mode, the Station monitors the RFID reader for an incoming identification card and until one is present, indicates a "Vacant" status to the Database. In addition, the Station is also periodically checking its onboard compass and publishing its heading to the Database. Lastly, the base charging pads do not pass current until appropriate wireless receiver pads are in range.
3. Power, Charging: The Station is properly connected to an appropriate power source, the RFID reader detects an ID card present, and the base pads are passing current due to the presence of appropriate receiver pads. In this mode, the Station publishes the ID of the currently present tag to the Database, while also continuing to publish its current heading. The Station is also supplying power to the base pads for powering the receiver pads present.

SCUTTLE:

1. Unpowered: In this mode, the SCUTTLE's systems and BeagleBone are not receiving necessary power to operate. In this case, the SCUTTLE does not support any communication, sensing, or actuating.
2. Powered, 3rd Party Task: In this mode, the SCUTTLE is receiving necessary power to operate its onboard BeagleBone Blue and supporting modules. Additionally the SCUTTLE has not yet entered the autonomous docking task delivered by our project. In this case, the SCUTTLE may be sitting idle or performing some other task defined by the User which lies outside the scope of our project.
3. Powered, Running Docking Task: SCUTTLE has necessary power to its BeagleBone Blue and supporting modules for proper functionality, and the User has launched our autonomous docking task. In this mode, the SCUTTLE autonomously navigates to and docks with the Station, or reports the reason for its inability to do so. Additionally, the SCUTTLE also publishes its battery voltage levels to the Database and continuously monitors the state of charging using the attached PCB. Lastly, once the SCUTTLE has fully charged itself at the Station it undocks to an appropriate distance and returns to Operation Mode 2 defined above.

Because the Internet of Things Database in Cayenne is a cloud based system, it has one mode of operation defined below:

IoT Database:

1. Recording and Reporting: In this mode, Cayenne records information being published to its monitored topics and displays the received data graphically to the user's account. This information is being sent to the Graphical User Interface, or GUI, regardless of whether or not the user is currently connected to the interface.

** The SCUTTLE and the charging station can operate exclusively in one mode at a time*

3.4. Users

The SCUTTLE Power Management System is intended for use by MXET department faculty and students. It enables students to learn more about IoT communication and autonomous vehicles. It also expands the electronic platform's capabilities and functionality by acting as a foundation for expanding into fleet operations. The system is intended to make the SCUTTLE's charging process more convenient for the user as well as allow for long repeatable missions since charging can be performed without powering down the robot.

4. Functional Requirements

1. SCUTTLE has autonomous docking capability within a specified range and unobstructed path to the station
2. Charging Station charges any SCUTTLE (with attached module) when docked
3. Charging Station identifies which SCUTTLE is docked
4. Charging Station and SCUTTLE communicate wirelessly to IoT database
5. SCUTTLE automatically stops charging when the batteries are completely charged
6. Charging Station indicates occupancy status to IoT database
7. SCUTTLE indicates battery voltage levels to IoT database
8. IoT Database records and reports occupancy status of Station including SCUTTLE ID, and battery voltage levels to a user through an easily interpretable GUI

5. Performance Specifications

CATEGORY	SPEC	VALUE	UNIT
Charging Station			
	Charge Coil Supply	5	Volts, DC
	Charge Time	1.5	Hours (or less)
	Identification Method	RFID	ISO-15693
	Identification Distance	0.15	m (maximum)
	Database Update Delay	30	Seconds (or less)
	Communication Protocol	IEEE 802.11b	N/A
	Unit Weight	9	kg (or less)
	Unit Height	0.45	m (or less)
	Unit Depth	0.61	m (or less)
	Unit Width	0.45	m (or less)
	Impact Velocity (w/Scuttle)	0.2	m/s (or less)
	MCU Supply Power	5	Volts, DC
	Charging Station Connection Type	Female USB-A 2.0	N/A
	Maximum Allowable Charge Pads	3	pads

Figure 2.0: Charging Station Performance Specifications

CATEGORY	SPEC	VALUE	UNIT
Onboard Module			
	Docking Radius	1.5	Meter (or less)
	Station Exit Distance	1	Meter (no less)
	Status Update Delay	10	Seconds (or less)
	Battery Charge Supply	15	Volts, DC
	Unit Weight	0.22	kg (or less)
	Voltage Sensor Range	0-12	Volts, DC (minimum)
	Voltage Sensor Acceptable Error	2	% (maximum)
	Module Connection Type	Female Mico USB	N/A
	Maximum Allowable Charge Pads	3	pads

Figure 2.1: SCUTTLE OnBoard Module Performance Specifications

6. Functional Block Diagram and Flowcharts

6.1. Hardware Functional Block Diagram

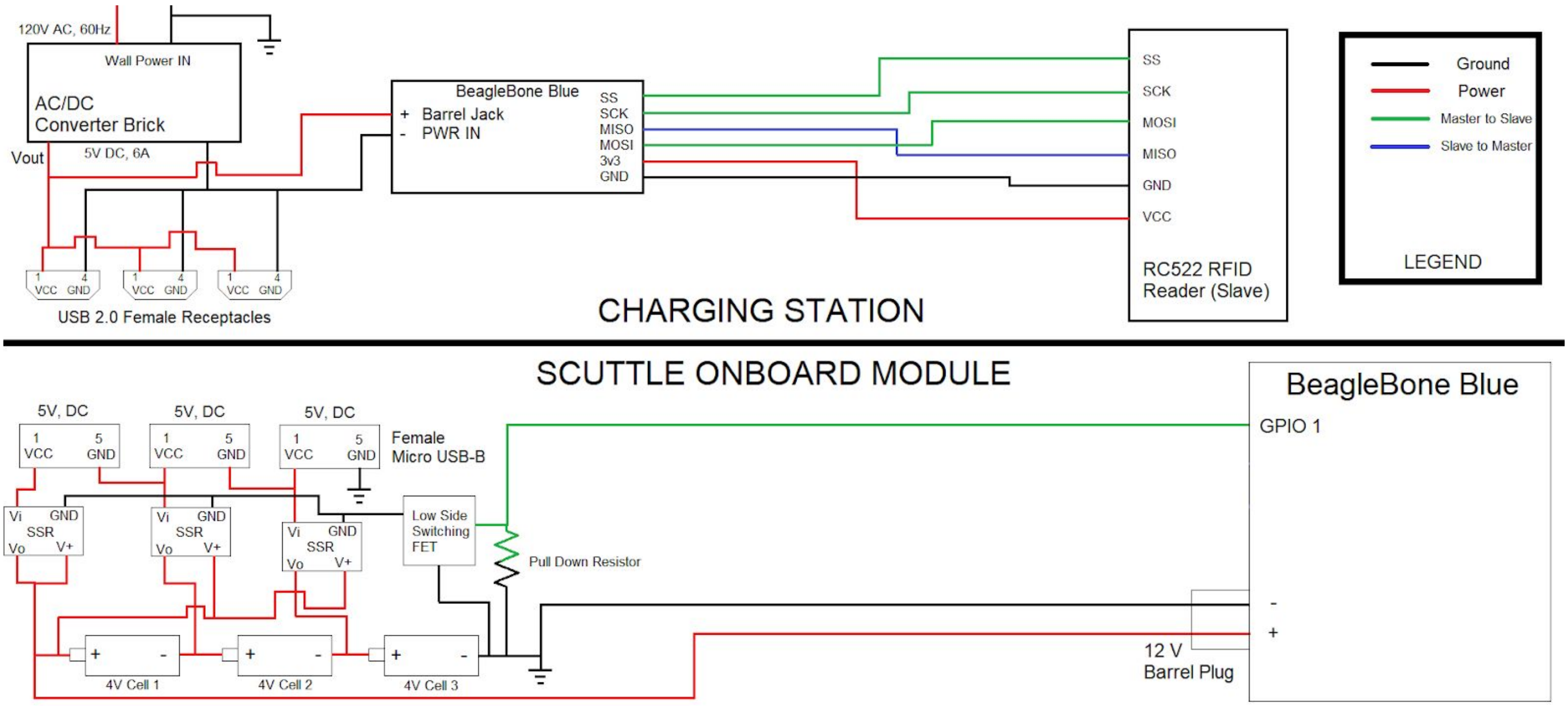


Figure 3.0: System Functional Block Diagram

The top half of Figure 3.0 represents the functionalities embedded within the Charging Station. From the left hand side of the diagram moving to the right, the Charging Station takes in standard United States wall outlet power which is approximately 120 Volts AC at 60 Hz via a power converter cable similar to those used for laptop computer chargers. The converter outputs power at 5 Volts D.C. at a maximum of 6 Amperes. This output is sufficient for supplying the 3 wireless charging base pads embedded on the front panel of the station which are connected via Micro USB cables to the power supply, as well as the BeagleBone Blue Mounted on the rear panel of the station and also connected via Micro USB. Lastly, the RFID interrogator, an RC522, mounted on the front panel of the station is connected via a 6 pin ribbon cable to the SPI port on the BeagleBone Blue and communicates using the same protocol. The BeagleBone Blue communicates as the Master while the RFID interrogator functions as a Slave. The RC522 receives a regulated 3.3 Volt power supply from the BeagleBone Blue as well as a clock signal for SPI communication.

The lower half of Figure 3.0 depicts the hardware functionalities for the SCUTTLE OnBoard module. Starting at the left side of the diagram, the 3 wireless charging receiver pads receive power from the Station when the SCUTTLE is docked. Each of these pads outputs 5 Volts D.C. at a maximum of 1 Ampere. This charging power is switched on or off by 3 solid state relays which are normally closed. Control of the relay position is provided by the GPIO port of the BeagleBone Blue connected to a low side switching FET. Because the relays are normally closed when the GPIO pin is set low, the relays stay closed and when the pin goes high the relays open which halts the flow of charging power and allows for an accurate voltage reading of the battery pack. This reading is taken via the BeagleBone Blue's barrel jack connector which reads the voltage across all 3 cells of the battery pack. Additionally, the batteries are connected in parallel to the S.O.B. via a 4 pin LiPo connector which provides balanced charging at a difference of 5 Volts per cell.

6.2. Docking Sequence Software Flowchart

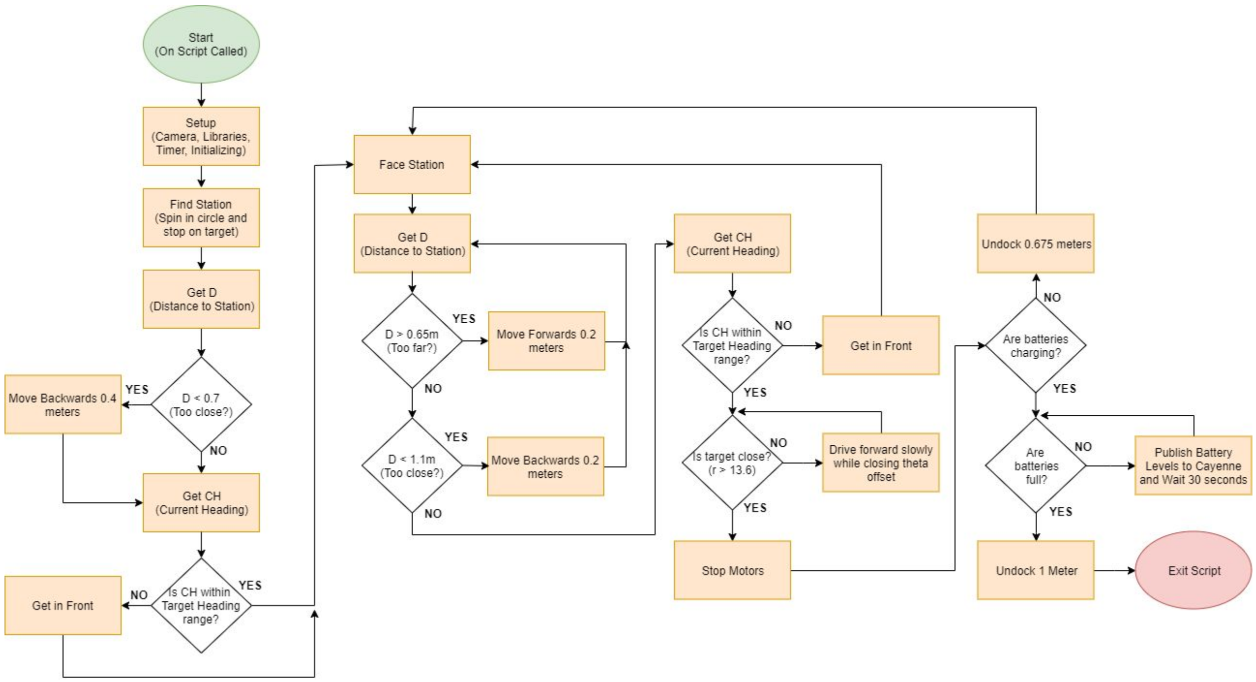


Figure 3.1 - Docking Sequence Software Flowchart

Figure 3.1 above describes the process that the SCUTTLE undergoes to autonomously dock at the charging station. The user can start this process by importing L3_Dock into their code and calling the Dock() function.

On startup, the SCUTTLE's sensor and motor control libraries are loaded which takes some time. The SCUTTLE then begins capturing an image feed as it rotates its body to scan for the station. Once the station is found, the SCUTTLE then corrects its orientation to fit the station's target in the center of its vision.

SCUTTLE then checks if it is too close to the station by checking the size of the target in its vision. If SCUTTLE determines the distance to be less than 0.7 meters, it backs up 0.2 meters. This step is to ensure that SCUTTLE avoids colliding with the station.

SCUTTLE then needs to check if it is already in alignment with the center of the station. This calculation is performed by checking its current compass heading and comparing it to the desired target heading range. If the SCUTTLE's current heading is not within the desired target heading range, then SCUTTLE uses trigonometry to calculate and drive a path to get in front of the station.

After this first sequence, SCUTTLE turns once again to face the station and determines if it has accidentally moved too close or too far away from the station. If SCUTTLE is less than 0.65 meters away from the station, it backs up 0.2 meters. If the SCUTTLE is more than 1.1 meters away from the station, it drives forward 0.2 meters. These checks are repeated until SCUTTLE is within the 0.65 - 1.1 meter range. After moving to its desired distance from the station, SCUTTLE determines if it is aligned with the station's center by getting its current compass heading and comparing it to the desired target heading range. If the SCUTTLE's current heading is not within the desired target heading range, then SCUTTLE uses trigonometry to calculate and drive a path to get in front of the station. Once SCUTTLE drives this calculated path, it continues to check if it is too close or too far away and if it is aligned with the center of the station until all conditions are met.

Once all conditions are met, SCUTTLE begins driving slowly towards the station, while closing theta offset, until it reaches the front of the station. Theta offset is defined as the angle between the center of the target and the center of SCUTTLE's vision. SCUTTLE determines that is has reached the station once the target's pixel radius reaches 13.6 pixels or more. Once SCUTTLE realizes it has reached the station, both motors stop.

After reaching the station, SCUTTLE waits for wireless charging to take place then checks if the batteries are charging. SCUTTLE determines if it is charging by comparing the closed relay voltage with the open relay voltage. If the closed relay voltage is higher than the open relay voltage then the wireless receiver pads are receiving power from the station and therefore the batteries are charging. If the SCUTTLE determines it is not charging, then SCUTTLE reverses 0.675 meters away and restarts the docking process until SCUTTLE is properly charging.

Once SCUTTLE is properly charging, SCUTTLE waits at the charging station while checking its charging status and updating its battery levels to the Cayenne IoT database until the batteries are fully charged. SCUTTLE determines it is fully charged once the battery pack voltage reaches 12V. Once SCUTTLE's battery pack voltage reaches 12V, SCUTTLE will undock 1 meter from the station which stops charging and the script will exit.

6.3. Charging Station RFID Software Flowchart

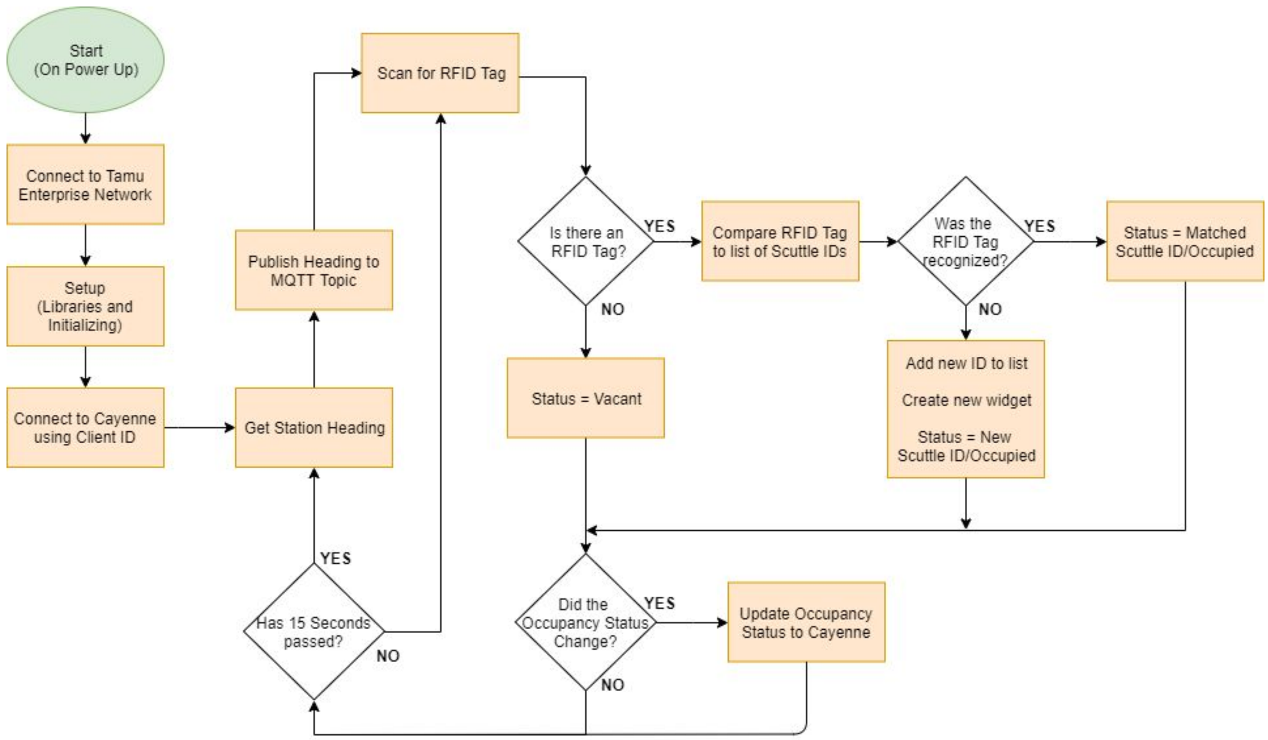


Figure 3.2 - Charging Station RFID Software Flowchart

Figure 3.2 above displays the software flowchart for the charging station's SCUTTLE identification process using RFID, and compass heading communication with an MQTT topic. Once the charging station has been plugged into the wall, its Beaglebone Blue starts this script. It first connects to the TAMU Wi-Fi network, initializes Cayenne IoT and RFID libraries, and connects to Cayenne. Once connected, the charging station's Beaglebone Blue uses the internal compass to determine a heading. This heading is published to an MQTT topic that the SCUTTLE robots will subscribe to when docking with the station. The charging station then scans for the SCUTTLE's passive RFID tag using a RC522 RFID sensor. If a tag hasn't been detected, the status is set to vacant and published to the database. Once an RFID tag has been detected the script will compare the detected RFID tag to a list of already recognized SCUTTLE ID's. Next the charging station's vacancy status is set to occupied. If the ID wasn't recognized the script automatically adds that SCUTTLE's ID to the list, and then the vacancy status is set to occupied. Afterwards, the occupancy status is updated on the Cayenne IoT interface. This loop continuously publishes compass headings, scans for additional RFID tags, and updates vacancy status accordingly.

6.4. SCUTTLE Battery Level Software Flowchart

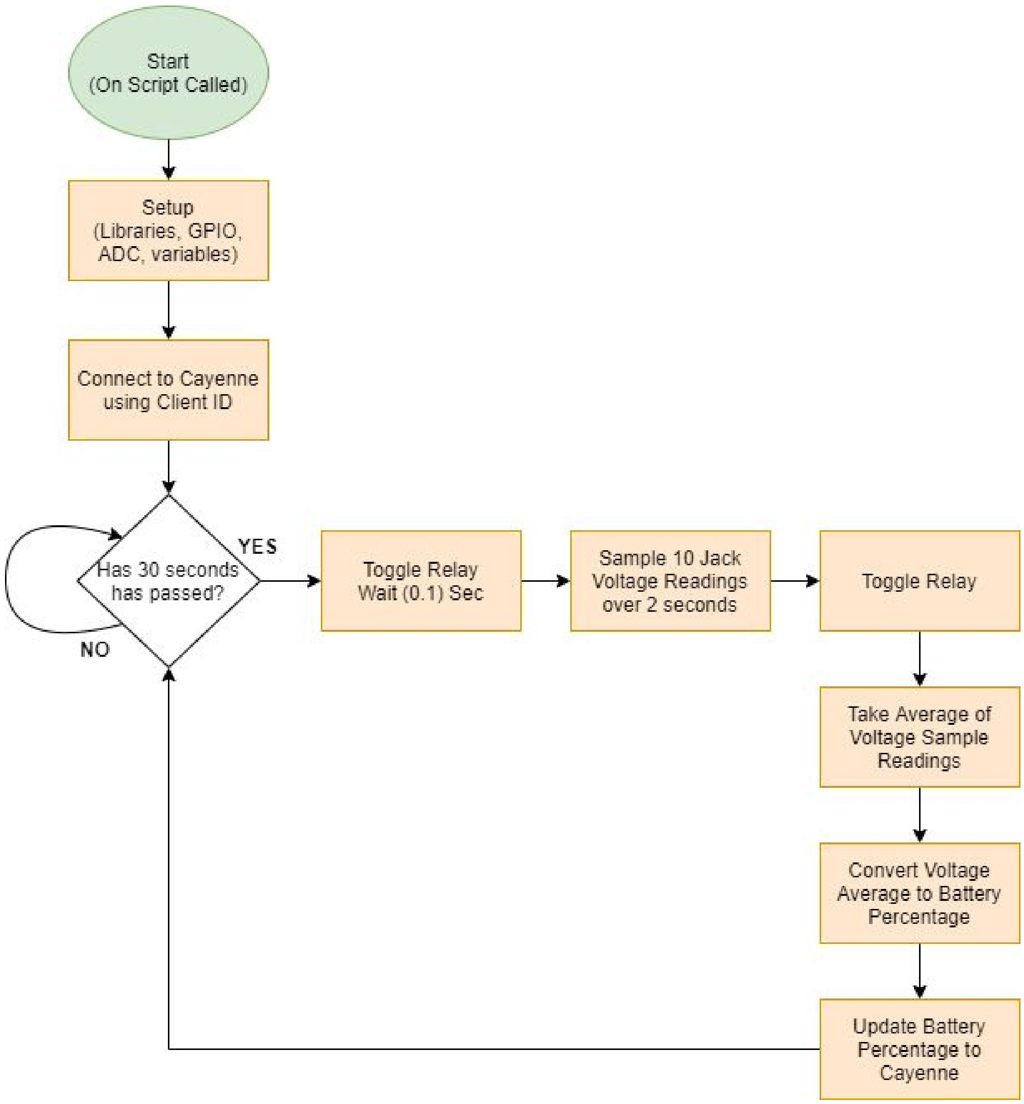


Figure 3.3 - SCUTTLE Battery Level Software Flowchart

The SCUTTLE's battery level software flowchart is seen above in Figure 3.3. The script starts by loading all GPIO, ADC, and other additional libraries necessary for I/O control, and then connects to Cayenne. Every thirty seconds the script opens the relays, waits ten milliseconds to let the relay open, samples ten barrel jack voltage readings over two seconds, closes the relays, calculates an average of the voltage sample readings, converts that result to a battery percentage, and updates this battery percentage to the Cayenne IoT interface.

7. Schematics

7.1. SCUTTLE On Board Module Schematic

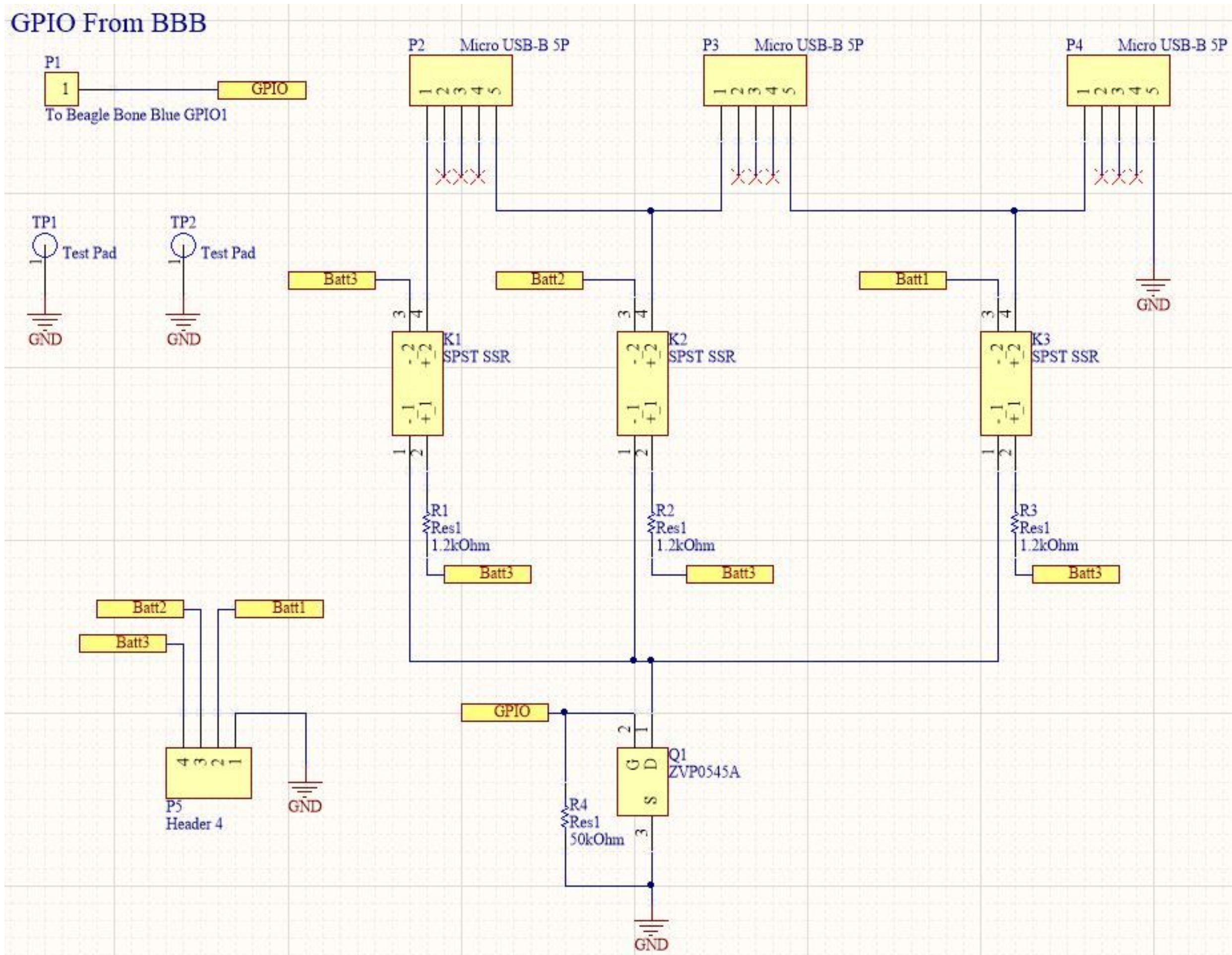


Figure 4.0 - SCUTTLE On Board Module Schematic

Figure 4.0 depicts the schematic for the SCUTTLE OnBoard module PCB which is mounted on the inside of the front rail on the robot and is responsible for receiving, supplying, and regulating charging power flow to the SCUTTLE's batteries.

7.2. Charging Station PCB Schematic

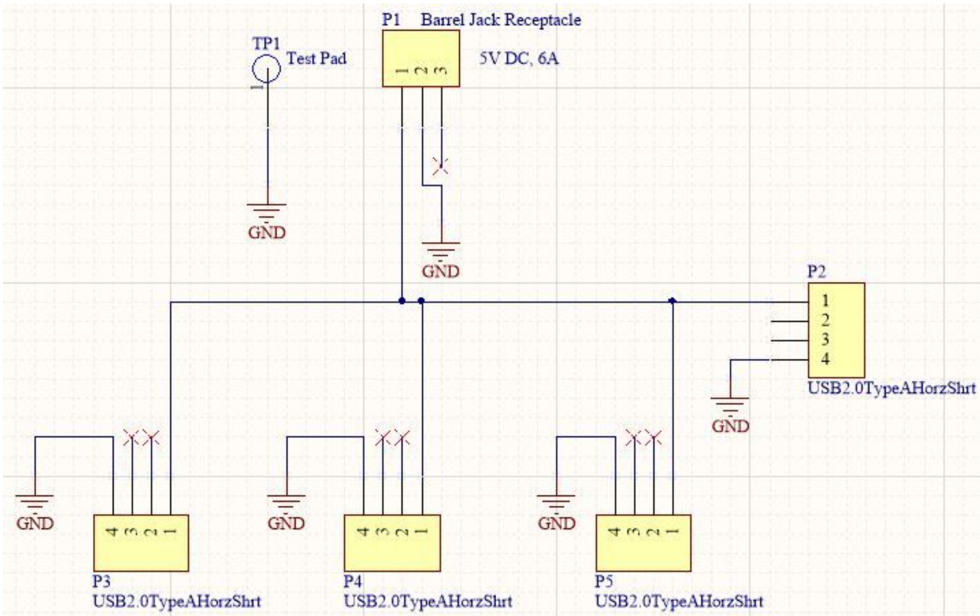


Figure 4.1 - Charging Station PCB Schematic

Figure 4.1 depicts the schematic for the Charging Station PCB which is mounted on the inside of the back panel of the charging station. This board is responsible for receiving power from the barrel jack connector on the power supply cable and distributing it to the BeagleBone Blue and the 3 wireless charging base pads.

8. Layouts

8.1. SCUTTLE On Board Module Beta Revision

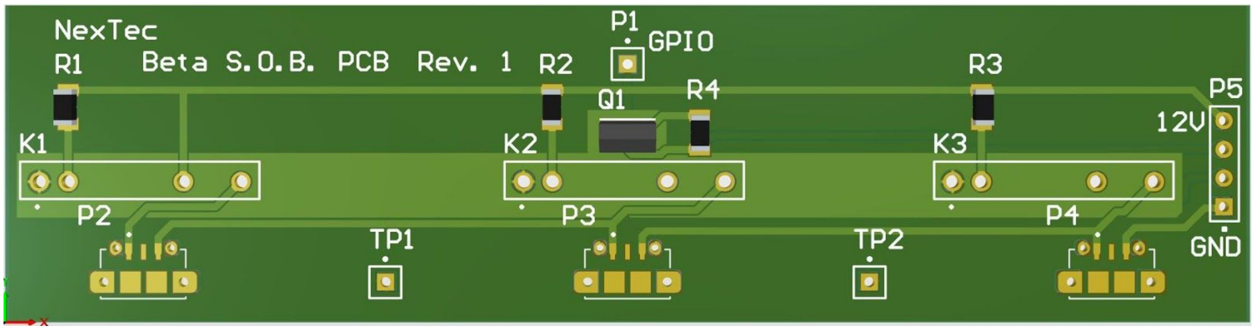


Figure 5.0 - SCUTTLE On Board Module Beta Revision Layout

Figure 5.0 depicts the SCUTTLE OnBoard module PCB's layout for connecting the necessary components. The profile of this layout allows for a proper and snug fit matching the mounting location of the SCUTTLE's front rail. Additionally, it offers convenient placement for connections for the GPIO, LiPo, and receiver pad cables. Lastly, large planes have been used for nets which could potentially have higher than normal current flow. Trace widths were also set to be sufficiently large enough to accommodate the typical 1 Amp of current. Furthermore, the layout of the board reflects a logical depiction of the proper connections to peripherals and components as well as minimizes the amount of criss crossing traces.

8.2. Charging Station PCB Beta Revision

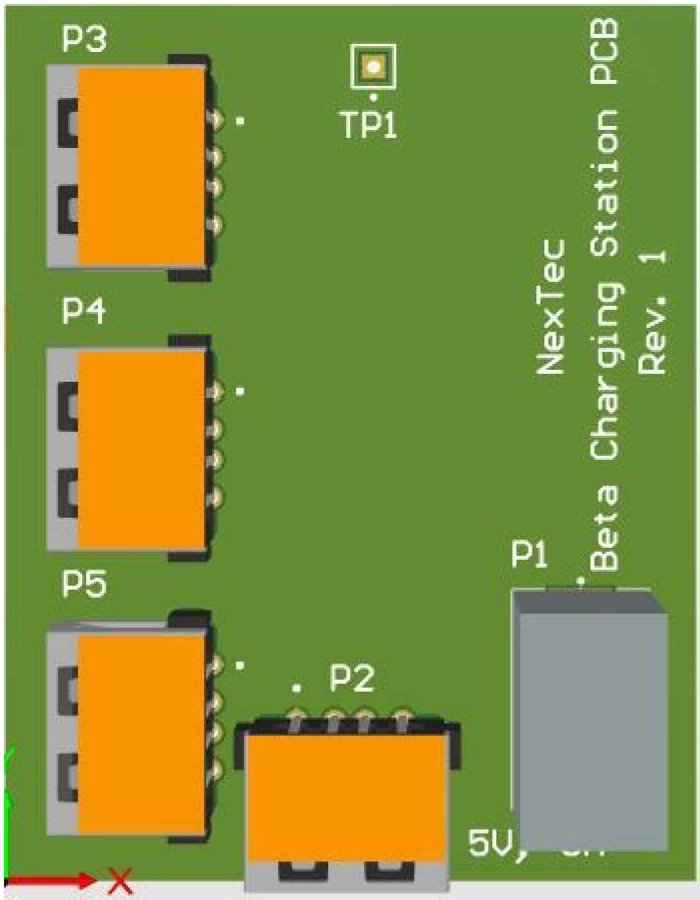


Figure 5.1 - Charging Station PCB Beta Revision

Figure 5.1 depicts the layout of components on the Charging Station’s PCB. This layout was chosen for its convenience in connecting the peripherals to the board as well as its ease for mounting within the charging station. Additionally, the current flow through this board can approach ranges close to 6 amperes. Therefore, the board consists of two large copper planes for positive and ground which provides thermal relief and reduced resistance.

9. Communication Interfaces/Protocols

9.1. MQTT

The SCUTTLE Power Management System uses the MQTT protocol, which decouples publishers from the subscribers, and client connections are always handled by a broker. Multiple project functionalities use MQTT; specifically for sending RFID information, charging station heading information, and SCUTTLE battery level information.

A client is an MQTT client that is a publisher or subscriber. A publishing client publishes messages, while subscribing clients subscribes to messages. An MQTT client is any device (from a microcontroller to a server) that runs an MQTT library and connects to an MQTT broker over a network. This project has two publishing clients: the Beaglebone Blue for the SCUTTLE and the Beaglebone Blue for the Charging Station.

The broker is responsible for receiving all messages, filtering the messages, determining who is subscribed to each message, and sending the message to these subscribed client. This relationship is shown in Figure 6.0 below.

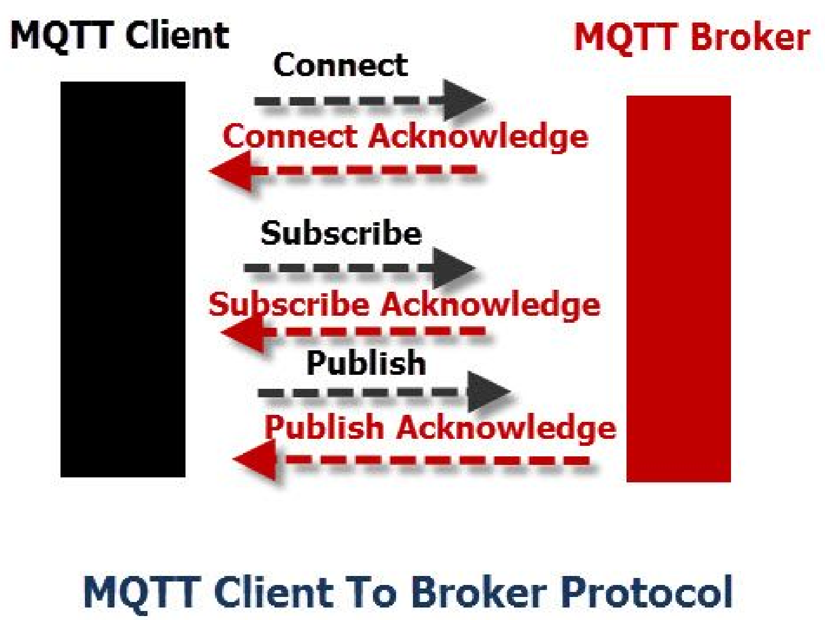
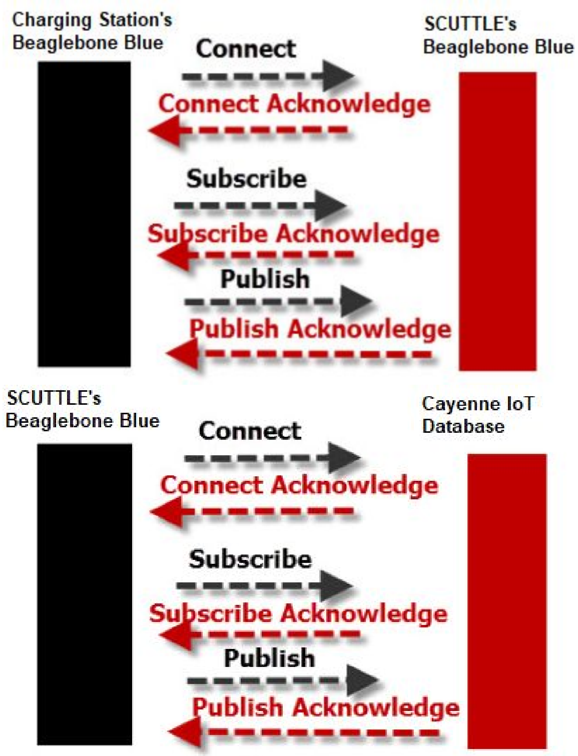


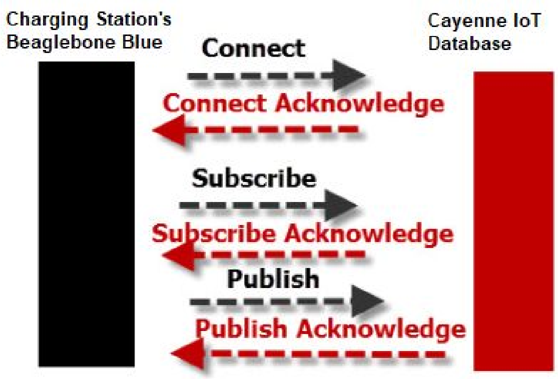
Figure 6.0: Client to Broker Relationship

The MQTT connection shown in the figure above is always between a client and a broker. The client sends a CONNECT message to the broker. The broker then responds with a CONNACK message and a status code. Then the client will send a publish/subscribe message, and the broker will send a publish/subscribe ACK message back until the connection is closed. It is important to note that brokers often have a multitude of clients instead of only one.



The specific publisher-subscriber relationships within the scope of this project are shown to the left. On the top, Figure 6.1 describes the relationship between the Charging Station's Beaglebone Blue and the SCUTTLE's Beaglebone Blue when the charging station is publishing its heading to the SCUTTLE. Thus, the SCUTTLE is a subscriber to the charging station's heading MQTT topic. This functionality is running on the Charging Station, however the SCUTTLE does not make use of this information for its docking sequence. Instead, the SCUTTLE relies on calibration from the user to supply the Station's heading information according to the SCUTTLE's own compass readings. During testing, we found this communication to be beneficial for docking because it allows the user to move the Station without needing to recalibrate the compass. However, because the onboard compass is not very robust, this introduced more error into the system and resulted in an inaccurate docking sequence. Therefore, even though we have created this functionality we do not use it in our prototype to limit the amount of introduced error. If more accurate and robust compasses are used in the future of this system, this functionality could easily be restored and taken advantage of in the next iteration.

In the middle, Figure 6.2 describes the relationship involved with reporting battery levels to Cayenne. The SCUTTLE's Beaglebone Blue is responsible for sending this information, and Cayenne is subscribed to the associated topic.



Lastly, Figure 6.3 on the bottom describes the relationship for the SCUTTLE identification process. In this example, Cayenne is subscribed to the Beaglebone Blue's topic for identification information received from the MFRC522 card reader. This information is displayed to the user on Cayenne's IoT interface for the user along with the battery levels from the SCUTTLE.

Figures 6.1,6.2,6.3: MQTT Relationships

9.2. SPI

The SCUTTLE Power Management System contains a RC522 RFID reader that is able to scan any SCUTTLE's passive RFID tag. The RC522 communicates with the charging station's Beaglebone Blue using Serial Peripheral Interface (SPI) communication.

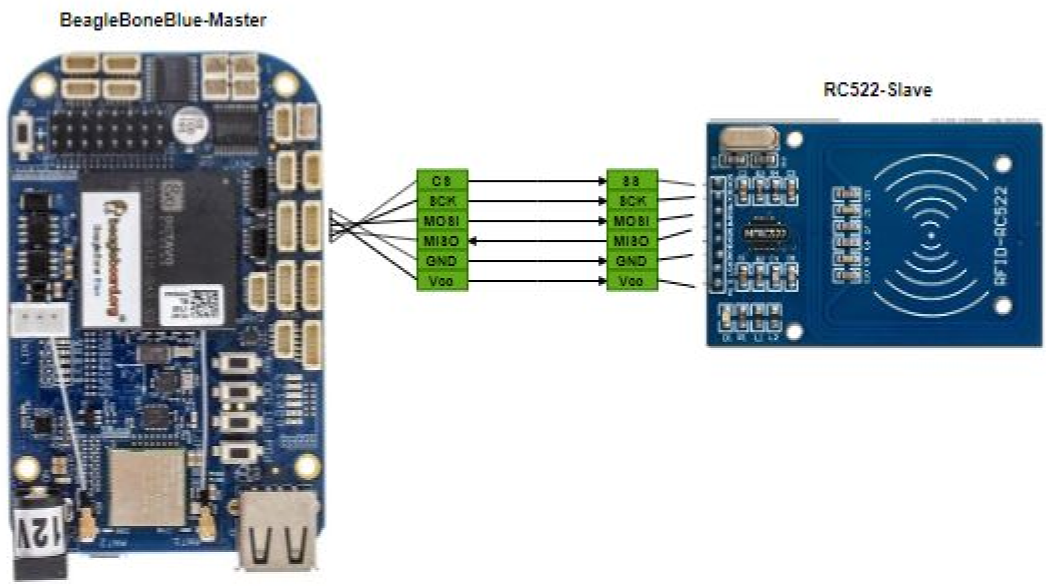


Figure 6.4: BeagleBone Blue/RC522 Pin Diagram

The pinout diagram shown above shows the configuration for the master to slave SPI communication. The BeagleBone Blue microcontroller acts as the master device and the RC522 acts as a slave. SPI is a synchronous communication protocol, meaning the clock signal synchronizes the output of data bits from the master to the sampling of bits by the slave. The master device sends the synchronous clock signal to the slave through the SCK pin. The master then selects and activates the slave device by switching the CS pin to a low voltage state. Once activated, the master sends the data one bit at a time to the slave along the MOSI line. The slave reads the bits as they are received. If a response is needed the slave returns data one bit at a time to the master along the MISO line. The master then reads the bits as they are received. The RST line can be used to reset the slave device if problems occur. Understanding the SPI communication protocol was necessary in understanding how to communicate with the RC522 active RFID reader. An example diagram of how SPI communications works is shown in Figure 6.5 below.

Figure 3.2: SPI Communication Protocol Diagram

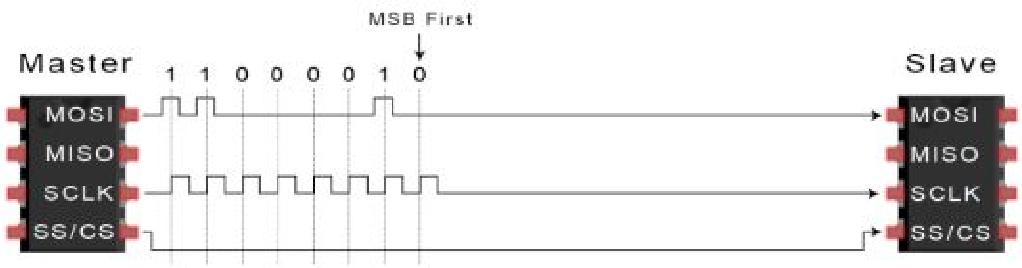


Figure 6.5: SPI Communication Protocol Diagram

10. Mechanical Designs

10.1. Charging Station

Figure 7.0: Charging Station Front View

Figure 7.1: Charging Station Rear View

The figures above depict the SCUTTLE Power Management System Charging Station. Many factors were taken into consideration when designing the Charging Station such as: space for the charging pads, RFID reader, and target on the front of the station, space for the BeagleBone Blue, Charging Station PCB, and all connections for electronics inside the station, form factor of the Charging Station itself, price, reproducibility, portability, and the ability for the Charging Station to withstand the impact of SCUTTLE mobile robot during the docking process.

The original design of the Charging Station was intended to be a 3D printed enclosure, but after considering the reproducibility of the design, and the consistency of 3D printing, a more “off-the-shelf” design approach was taken. Although this increased the overall cost of the Charging Station, the design has proven to be effective, and capable of meeting the functional requirements of the project.

10.2 SCUTTLE On Board Module

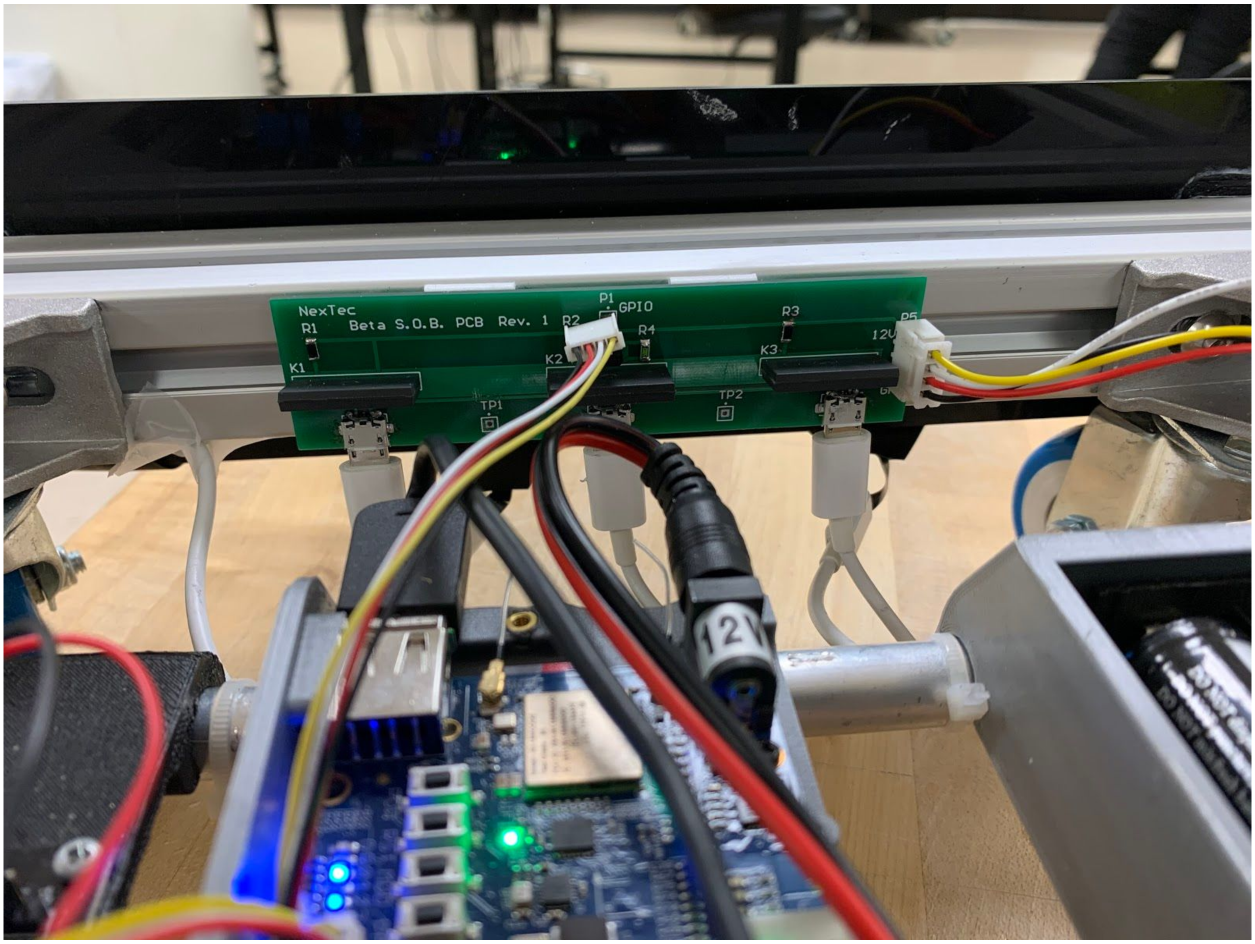


Figure 7.2: S.O.B. PCB and Connections to SCUTTLE

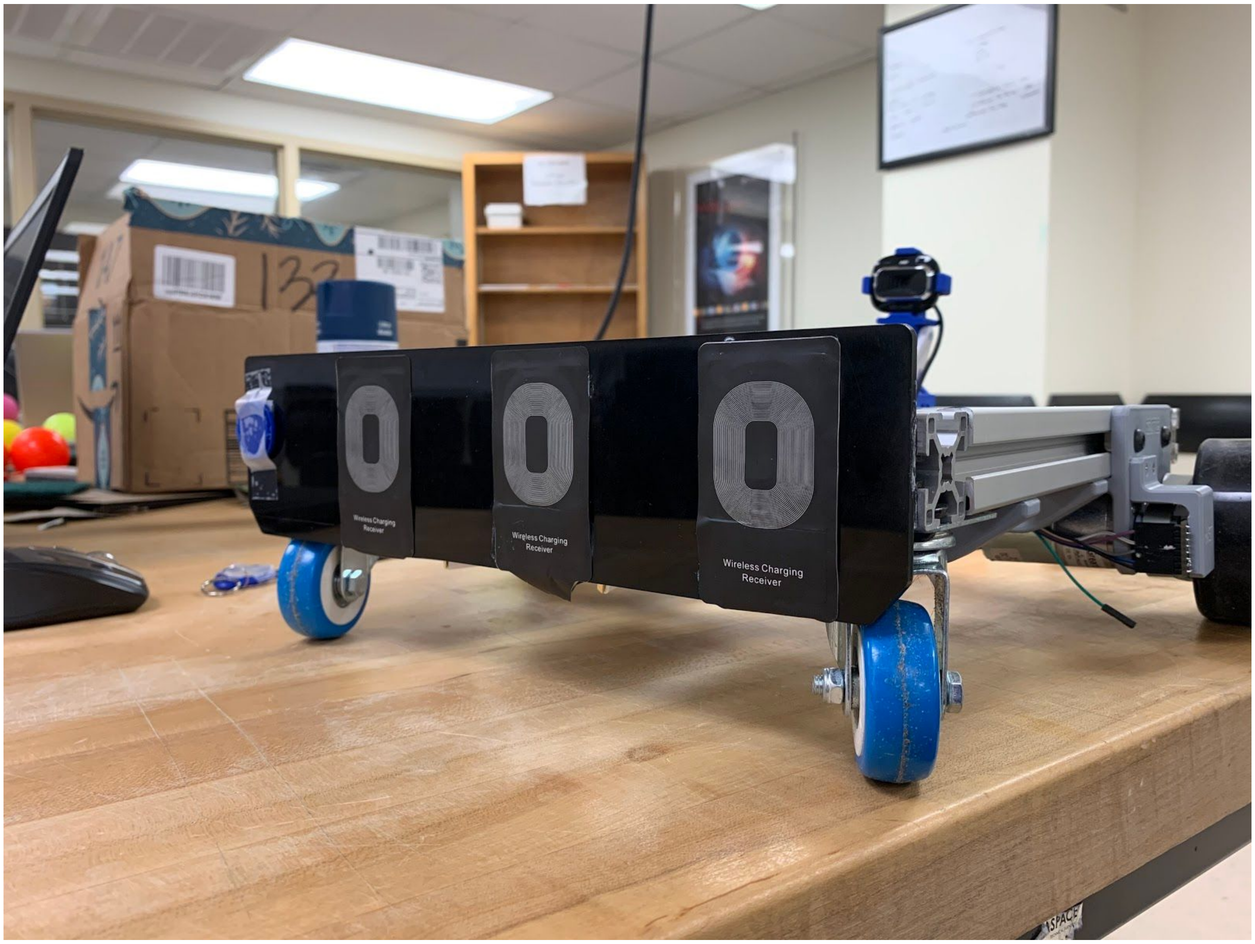


Figure 7.3: S.O.B. Front Mounting Panel Including Wireless Receiver Pads and RFID Tag

The images above depict the mechanical mounting designs for the S.O.B. At the forefront of these designs were modularity and ease-of-use. The front panel can easily be removed by unplugging the wireless receiver pads and sliding it off of the front rail. Additionally, the PCB can be easily removed by unplugging the connections to the SCUTTLE and pushing on the tabs while gently pushing them off of the rail. Furthermore, these mounting designs are easily replicable with 3D printed parts and adhesive.

11. Beaglebone Blue Microcontroller

The Beaglebone Blue microcontroller was chosen for both the SCUTTLE and the charging station because of its PWM, SPI, I2C, GPIO, and Wi-Fi capabilities. Additionally, this microcontroller was an off-the-shelf microcontroller already used and understood by students and faculty of the MXET department.

11.1. PWM

The Beaglebone Blue has four DC motor drivers on-board, which is necessary for SCUTTLE's motor control functionality.

11.2. SPI

The Beaglebone Blue has two SPI ports, which allows the charging station's Beaglebone Blue to communicate with the RC522 RFID reader. These ports have the select, SCK, MOSI, MISO, VCC, and GND pins grouped into a 6-pin connector that is wired to the RC522.

11.3. I2C

The Beaglebone Blue contains an I2C bus that is used to communicate to the encoders, which in the scope of our project, provides feedback to the motor control system as the SCUTTLE navigates itself to the station.

11.4. GPIO

There are two GPIO ports on the Beaglebone Blue that control 8 separate I/O wires. The relays on the SCUTTLE On Board module are controlled by these GPIO pins. In order to attain a reading of SCUTTLE's battery levels, the module activates relays that are wired to the SCUTTLE's battery pack via a LiPo connector.

11.5. Wi-Fi

The Beaglebone Blue contains the TI WiLink 8 802.11b/g/n chip that has Bluetooth4.1/BLE connectivity. This chip allows the Beaglebone Blue to connect to the university's Wi-Fi network and upload sensory data to the Cayenne IoT database..

12. Test Plan

12.1. Background

The SCUTTLE Power Management System is a system that can autonomously dock a SCUTTLE with a charging station, charge the batteries on that SCUTTLE, undock after charging, and return control of that SCUTTLE back to the user. The system also uploads battery level information and station occupancy status to the Cayenne IoT interface. NexTec has agreed to deliver one (1) functioning prototype system which meets the functional requirements of the system that were agreed upon by both all stakeholders and NexTec. These functional requirements are again listed below:

1. SCUTTLE has autonomous docking capability within a specified range to the station
2. Charging Station charges any SCUTTLE (with appropriate modifications) when docked
3. Charging Station correctly identifies which SCUTTLE is docked
4. Charging Station and SCUTTLE communicate wirelessly to database
5. SCUTTLE automatically stops charging when the battery is completely charged
6. Charging Station indicates occupancy status to online database
7. SCUTTLE indicates battery charge levels to online database
8. Online Database records and reports occupation status, SCUTTLE identification, and battery charge levels to a user through a graphical interface

This test plan outlines the demonstrations performed in order to indicate to all parties that the SCUTTLE Power Management System meets all of its functional requirements and thus qualifies as a functioning prototype system. Additionally, each functional requirement will have **PASS/FAIL** conditions discussed below.

12.2. Tests

#1 - Autonomous docking capability

The SCUTTLE is able to autonomously dock itself to the charging station within a 1.5 meter arc of the station, from at least 45 degrees away from the front face of the station. This is achieved using the webcam sensor as well as the magnetometer for attaining heading information relative to the Earth's magnetic North. The range of docking is measured using a measuring tape. Proper docking alignment is determined by a multimeter reading of the charging power supplied to the batteries.

Testing/Validation:

SCUTTLE must navigate itself to the charging station successfully when placed in the specified range of the station free of any obstructions, and if not, print out an error code and notify the user why it cannot dock correctly. The SCUTTLE must be placed at least 0.5 meters away from the station.

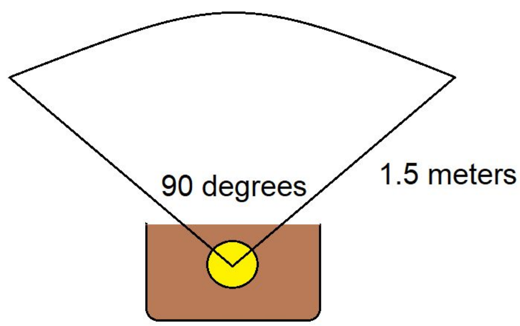


Figure 9.0 - Specified Autonomous Docking Range (Not to scale)

Pass/Fail Criteria:

Pass: The SCUTTLE successfully navigates itself to the station and begins charging. If the SCUTTLE encounters an error during the autonomous docking process, the terminal will display an error code, notifying the user what went wrong during the docking process.

Fail: The SCUTTLE cannot autonomously dock with the station and gives no indication as to what caused the failing condition.

#2 - Charging Station charges any properly equipped SCUTTLE:

Testing/Validation:

When docked at the Charging Station, the SCUTTLE must be able to receive sufficient power from the base pads via the receiver pads in order to charge its on-board batteries within the time frame specified. The fullness of the batteries is determined by a multimeter reading.

Pass/Fail Criteria:

Pass: When docked, the SCUTTLE's batteries charge from near 0% to 100% within the amount of time specified.

Fail: SCUTTLE's batteries are unable to fully charge after being properly docked at the station within the specified time.

#3 - Charging Station identifies any properly equipped SCUTTLE:

Testing/Validation:

The RC522 communicates RFID data to the charging station's Beaglebone Blue identifying any docked SCUTTLE, so long as it has a passive RFID tag in the proper mounting location. Proper identification is determined by comparing the ID tag card number to the received ID number on the Station's BeagleBone.

Pass/Fail Criteria:

Pass: The charging station is able to identify any docked SCUTTLE with a passive RFID tag. If it does not have an identified passive RFID tag, it will assign it an identity automatically.

Fail: The charging station is unable to identify a SCUTTLE with a tag properly equipped.

#4 - Charging Station and SCUTTLE communicate wirelessly to database:

Testing/Validation:

The SCUTTLE's and the charging station's Beaglebone Blue connects to the tamulink-wpa university Wi-Fi network and publishes to topics on the Cayenne IoT Database. Communication is verified by monitoring the interface on the database as various sensory parameters change, e.g. the ID card reading from the Station or SCUTTLE's battery voltage.

Pass/Fail Criteria:

Pass: The SCUTTLE and charging station can successfully connect to the university Wi-Fi network and can upload sensory information to the Cayenne IoT Database.

Fail: The SCUTTLE or charging station can not successfully communicate with, or upload sensory information to, the Cayenne IoT database.

#5 - SCUTTLE automatically stops charging when battery levels are full:

Testing/Validation:

The SCUTTLE autonomously ceases charging when its batteries are completely charged. The halting of the charging process is verified by a multimeter reading of the SCUTTLE OnBoard module connections.

Pass/Fail Criteria:

Pass: The SCUTTLE no longer applies charging power to the batteries and returns to the previously running task once its batteries are full.

Fail: The SCUTTLE fails to automatically halt its charging process when the batteries have reached their full capacity.

#6 - Charging station indicates occupancy status to online database:

Testing/Validation:

The charging station publishes an accurate occupancy status to the Cayenne IoT database for display to the user. Verification is performed by comparing the ID card present at the station to the ID number displayed on the Database's GUI.

Pass/Fail Criteria:

Pass: The charging station is able to publish whether the station is "Vacant" or "Occupied with "SCUTTLE X" to the GUI present on the Cayenne IoT database.

Fail: The SCUTTLE is unable to successfully publish occupancy information to the Database.

#7 - SCUTTLE indicates battery charge levels to online database:

Testing/Validation:

The SCUTTLE publishes its battery level percentage to Cayenne for the user. Accuracy to the provided specification is calculated using a multimeter reading and comparing to the value shown in the Database.

Pass/Fail Criteria:

Pass: The SCUTTLE publishes battery pack voltage percentage to the GUI within the specified range of acceptable error.

Fail: The SCUTTLE is unable to successfully publish battery level information to the Database within the provided specification.

#8 - Online Database records and reports occupation status, SCUTTLE identification, and battery charge levels to a user through a graphical interface:

Testing/Validation:

The Cayenne IoT database's dashboard maintains a time log of battery charge levels, occupancy statuses, and SCUTTLE identification.

Pass/Fail Criteria:

Pass: The Cayenne IoT Database's Dashboard has accurately logged battery charge levels and occupancy statuses for as long as specified. Verification is conducted through observation of the Database's logs.

Fail: The information displayed on the dashboard over time is inaccurate or does not meet the specified criteria.

13. Test Report

1. **Autonomous docking capability:**
   PASS SCUTTLE successfully docked itself and began charging. However, after running this test several times one potential issue arose. The onboard compass is very prone to even slight fluctuations in the magnetic field of the environment causing it to occasionally incorrectly calculate its distance to the station. If given enough time it will eventually dock, usually only taking one extra step before final approach.

2. **Charging Station charges any properly equipped SCUTTLE:**
   PASS When properly aligned, the SCUTTLE charges its batteries within a specified amount of time and removes itself from the station once they have reached 100%. However, if the batteries are new, as was the case with one of our tests, the batteries will take longer to charge than originally calculated. The older batteries we had been using all year charged within spec.

3. **Charging Station identifies any properly equipped SCUTTLE:**
   PASS Whenever a SCUTTLE is properly aligned the Station recognizes its attached RFID card and assigns it an easy to understand integer. Switching out the ID tag also updates accordingly.

4. **Charging Station and SCUTTLE communicate wirelessly to database:**
   PASS During the Battery Charge testing the voltage values in the Database were updating in real time and within spec. During the RFID test the occupancy status and ID of the docked SCUTTLE also updated in real time. Additionally, when a SCUTTLE with an ID that has not yet been seen by the Station docks, the Station automatically creates a new channel and GUI display for the new ID in the Database.

5. **SCUTTLE automatically stops charging when battery levels are full:**
   PASS During the Battery Charge testing, the SCUTTLE automatically reverses away from the station, thus disconnecting the power supply to the batteries, whenever the measured voltage reached 100%. This protects the batteries from over-charging.

6. **Charging station indicates occupancy status to online database:**
   PASS The Station displays both a Vacant and SCUTTLE ID widget in the Database, whenever a SCUTTLE is docked, the ID widget lights up and the ID of the SCUTTLE docked is displayed. Whenever no SCUTTLE is docked, the Vacant widget lights up and the other widgets dim.

7. **SCUTTLE indicates battery charge levels to online database:**
   PASS The SCUTTLE updates its battery voltage percentages to the GUI located in the Cayenne database as performed during the Battery Charge testing.

8. **Online Database records and reports occupation status, SCUTTLE identification, and battery charge levels to a user through a graphical interface:**
   PASS As discussed in previous tests the Cayenne IoT databases displays all the described information in an easy to read GUI. Additionally graphs of all of the information can be shown if the user chooses to do so. However, the information is only stored as long as the device is connected to the Database. Power cycling the devices will reset the charts.

14. Expenses

Category	Original Estimate	Current Estimate	Cumulative	Status
PCB Parts	$68.42	$190.74	$190.74	-$122.32
Enclosures	$152.95	$360.46	$360.46	-$207.51
Misc Parts	$25.39	$114.94	$114.94	-$89.55
PCB Fabrication	$100.00	$11.10	$11.10	+$88.90
Shipping	$200.00	$305.62	$305.62	-$105.62
Total	$546.76	$982.87	$982.87	-$436.10

Figure 10.0 Expenses

The table shown in Figure 10.0 depicts the total amount of money spent on the production and development of the SCUTTLE Power Management System. In all categories except PCB fabrication, we exceeded our projected expenses predicted in ESET 419. The main driver of the unexpected higher expenses in the *"Enclosures"* and *"Misc Parts"* categories stem from a design change from our customer at the beginning of ESET 420. Our original design for enclosures were to be primarily fabricated utilizing 3D printing, but after considering the complexity and reproducibility of this design, our customer opted for an "off-the-shelf" parts approach. Additionally, the over expenditures in the *"PCB Parts"* and *"Shipping"* categories can be attributed to lack of planning, and not accounting for faulty parts or parts that were damaged during testing. Overall, we are satisfied with the total money spent on the project considering the changes in our design.

15. Bill of Materials

Store	Category	Part	PN	Price from Store	Unit Price of 1	Amount Needed to Build 1 Prototype	Cost for 1 Prototype	Amount Needed for 100	Unit Bulk Price	Cost for 100 Prototypes
				Off-The Shelf: Hardware						
McMaster-Carr	Charging Station	T-Slotted Framing Single Rail, Silver, 30mm (2ft. Length) (for frame)	5537T97	$9.76	$9.76	2.00	$19.52	200.00		$1,952.00
McMaster-Carr	Charging Station	T-Slotted Framing Single Rail, Silver, 30mm (1ft. Length) (for frame)	5537T98	$5.99	$5.99	2.00	$11.98	200.00		$1,198.00
Amazon	Charging Station	PZRT 3030 Series Aluminum Profile Connector Set (to connect frame)	B07BQR7WX8	$9.90	$9.90	1.00	$9.90	100.00		$990.00
McMaster-Carr	Charging Station	Steel Pan Head Phillips Screw, M2.5 x 0.45 mm Thread, 6 mm Long, 1 Pack (for RFID reader, Beagle Bone, and Charging Station PCB)	92005A066	$4.66	$0.05	10.00	$0.47	1000.00	$4.66(100)	$46.60
McMaster-Carr	Charging Station	Tapered Heat-Set Inserts for Plastic, Brass, M2.5 x 0.45 mm Thread Size, 3.4 mm Installed Length 1 pack, (for Mounting RFID reader, BeagleBone, and Charging Station PCB)	94180A321	$11.19	$0.11	10.00	$1.12	1000.00	$11.19	$111.90
McMaster-Carr	Charging Station	Screws, M6 x 14 mm (for acrylic) pack of 100	91239A319	$11.26	$0.11	8.00	$0.90	800.00	$11.26	$90.08
McMaster-Carr	Charging Station	Heat Set Insert, Brass, M5 x 0.80 mm Thread Size, 6.700 mm Installed Length, package of 50 (for target)	94180A361	$12.42	$0.25	1.00	$0.25	100.00	$12.42(10)	$24.84
McMaster-Carr	Charging Station	M5-0.8 x 40 mm Phillips Pan Head Screw, pack of 10 (for Target)	90116A270	$9.22	$0.92	1.00	$0.92	100.00	$92.20	$92.20
McMaster-Carr	Charging Station	M5 Zinc-Plated Flat Washers pack of 100 (for Target)	91166A240	$2.42	$0.02	2.00	$0.05	200.00	$2.42(2)	$4.84
Home Depot	Charging Station	1 in. x 24 in. PVC Sch. 40 Pipe (for mounting Target, cut to 3.5 cm)	202300506	$2.34	$2.34	1.00	$2.34	6.00		$14.04
Amazon	Charging Station	Scotch Indoor Mounting Tape, 0.75-inch x 350-inches, White, Holds up to 10 pounds, 1-Roll (110-LongDC) (for Charging Pads Back Plate)	B009NP1OBC	$9.88	$9.88	1.00	$9.88	10.00		$98.80
Amazon	Charging Station	VELCRO Brand - Sticky Back Hook and Loop Fasteners| Perfect for Home or Office | 5ft x 3/4in Roll | Black (for Charging Pads)	B00006IC2L	$6.53	$6.53	1.00	$6.53	10.00		$65.30
Amazon	Charging Station	Mylec Spring/Summer 6 Pack Balls 6 Pack Spring/Summer Balls, Red/Orange/Pink (Target, Use Orange if using Black Acrylic)	B01LFVL9GG	$15.99	$2.67	1.00	$2.67	100.00		$799.00
						Sub Total	$66.52		Sub Total	$5,487.60
Mouser	MPU	BeagleBone Blue	95Y0640	$82.00 ($79.99 if purchasing 5)	$82.00	1.00	$82.00	100.00	$79.99(5)	$7,999.00
Amazon	RFID Reader and Tags	SunFounder RFID Kit Mifare RC522 RFID Reader Module with S50 White Card and Key Ring for Arduino Raspberry Pi (Comes with RFID tags for On Board Module)	B07KGBJ9VG	$6.99 (12.89 for 5)	$6.99	1.00	$6.99	20.00	$412.89(5)	$257.80
Amazon	Wiring BBB to RFID	Connector - JST SH 1.0 mm 6-pin pack of 10 (for RFID reader)	B01IZWYK7I	$7.99	$0.80	1.00	$0.80	100.00	$7.99(10)	$79.90
Amazon	Charging Station	YI-BEN QI Wireless Charging Pad (includes micro USB cable)	5647450433	$11.99	$11.99	3.00	$35.97	300.00		$3,597.00
Amazon	On Board Module	Wireless Charging Adapter Qi Charger Receiver	B075XC5ZNT	$9.99	$9.99	3.00	$29.97	300.00		$2,997.00
Amazon	Wiring On Board Module	zdyCGTime 4 Inch Cellphone/Tablet USB Micro Male to Female Sync & Charging Extension Cable, 2/pack (connect from On Board Module PCB to Receiver Pads)	B071NR19BQ	$6.99	$3.50	3.00	$13.98	300.00	$6.99(2)	$1,048.50
Amazon	Wiring On Board Module/PCB	LATTECH 15 PCS 4 PIN JST XH Female Connector on One Side, pack of 15 (for modified battery pack)	B07PX14DVW	$7.98	$0.53	1.00	$0.53	100.00	$7.98(15)	$55.86
Amazon	Charging Station	5V/6A Power Supply	B0749558XV	$19.95	$19.95	1.00	$19.95	100.00		$1,995.00
						Sub Total	$190.19		Sub Total	$18,030.06
Amazon	Laser Cut	Charging Station - Front Panel	B01DYSTYBA	$70.72	$70.72	1.00	$70.72	100.00		$7,072.00
Amazon	Laser Cut	Charging Station - Back Panel	B01DYSTYBA			USE LEFTOVER ACRYLIC FROM FRONT PANEL				
Amazon	Laser Cut	Charging Station - Charging Pads Back Plate	B01DYS8S12	$19.80	$19.80	1.00	$19.80	100.00		$1,980.00
Amazon	Laser Cut	On Board Modubie - Receiver Pads/RFID Tag Plate	B01DYSSS12			USE LEFTOVER ACRYLIC FROM FRONT PANEL				
Amazon	3D Print	PLA Filament Printing Material (price per kg listed)	B07V4QQC58	$22.99	$22.99	1.00	$22.99	20.00		$459.80
JL PCB	PCB	Charging Station PCB (price listed without components)	N/A	$0.40	$0.40	1.00	$0.40	100.00		$40.00
JL PCB	PCB	SCUTTLE On Board Module PCB (price listed without components)	N/A	$1.02	$1.02	1.00	$1.02	100.00		$102.00
						Sub Total	$114.93		Sub Total	$9,653.80
Mouser	PCB Component	USB Connectors WR-COM USB Type A THT Horz Short	614104190121	$1.59	$1.59	4.00	$6.36	400.00	$0.953(100)	$381.20
Pololu	PCB Component	DC Power Adapter Barrel Jack	1139	$0.85	$0.85	1.00	$0.85	100.00	$0.65(100)	$65.00
						Sub Total	$7.21		Sub Total	$446.20
Mouser	PCB Component	USB Connectors 5P RECEPTACLE	ZX62D-B-5PA8(30)	$0.70	$0.70	3.00	$2.10	300.00	$0.462(100)	$138.60
Mouser	PCB Component	Solid State Relays - PCB Mount SinglePole Normally 60V/3.25A DC	CPC1705Y	$5.77	$5.77	3.00	$17.31	300.00	$4.22(100)	$1,266.00
Mouser	PCB Component	Thick Film Resistors 0.5watt 1.2Kohms 1% 100ppm	71-RCS12061K20FKE	$0.33	$0.33	3.00	$0.99	300.00	$0.112(100)	$33.60
Amazon	PCB Component	LATTECH 15 PCS 4 PIN JST XH Female Connector on One Side, pack of 15 (Note: These come in the pack of connetors from Amazon)	B07PX14DVW	-	-	-	-	-	-	See Above
Mouser	PCB Component	MOSFET N-Chnl 60V	ZVN4206A	$0.70	$0.70	1.00	$0.70	100.00	$0.38(100)	$38.00
Mouser	PCB Component	Thin Film Resistors - SMD 50kOhm,1206,0.1%,25p pm,125mW,150V	RN732BTTD5002B25	$0.94	$0.94	1.00	$0.94	100.00	$0.598(100)	$59.80
						Sub Total	$22.04		Sub Total	$1,536.00
						Total for 1 Prototype	$400.89		Total for 100	$35,153.66

Figure 11.0: Bill of Materials

16. Technical Merit

The SCUTTLE Power Management System achieves acceptable technical merit for an ESET Capstone project through its complexity in both electronic, mechanical, and software design. This Capstone project stands unique among previous projects in the department in that it explores the potential of wireless charging and IoT technology for the potential management of a fleet of autonomous robots. Additionally, this project brings cost effectiveness and minimal additional sensing and actuation while achieving functionality to the forefront of its design. Not only does this project serve as a foundation for potential commercial expansion but it also serves as a bolster to the education experience received by fellow Aggies at Texas A&M University.

Furthermore, the SCUTTLE Power Management System incorporates cutting edge technology currently being tested and developed in industry into the curriculum for students studying our project. Machine vision, Internet of Things communication, wireless charging, and fleet artificial intelligence are all technologies which are currently being expanded upon and tested in a variety of technologically advanced industries such as Amazon's drone deliveries, Tesla's self driving vehicles, and Google's smart home devices. Therefore, our project, when incorporated into the curriculum, will uniquely position TAMU students to have a significant impact in any of these industries by providing in-depth exposure to all of these topics at an extremely affordable cost.

17. Contact Info

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