Auto-Docking Cat Toy

ECE 445 Design Document, Spring 2019

Team 60 – Robert Malito, Yuhao Liu, Justin Li

TA: Soumithri Bala

Sponsor: Petronics, Inc.

I. Introduction

Objective:

Cats are one of the most commonplace pets in the world. The number of domestic pet cats in United States reached 94.2 Million in 2017[1]. With their owners busy at work, school, or on vacation cats are often left alone for extended periods of time. Studies have also shown that cats can experience loneliness when left alone[2]. Owners who worry about the emotional and physical wellbeing of their feline companions are always looking for something to keep their pets happy and entertained. An awesomely engaging cat toy called the Mousr has been developed and put into production by a startup company here on campus called Petronics[3]. Its small profile and nimble movement abilities make Mousr a very enticing toy for all felines. In 2018, Mousr was highlighted by the American Pet Product Association as the "Best New Cat Product" of the year.

While buyers are mostly satisfied with the Mousr product, the battery life has been addressed as the most limiting aspect of the device. Currently, the Mousr's battery can only support around 2 hours of continuous operation. Buyers of this product would like to be able to leave the Mousr to entertain their cats for extended periods of time when they leave for work or vacation. This is difficult due to the size constraints implied by cat's proclivity to play with small objects. Increasing the battery life by expanding the robot size will sacrifice the small profile and leave cats uninterested in the toy.

In order to solve this issue, Petronics came up with an idea to let the robot automatically go back to a charging dock when its battery level is low. We purpose a feasible way to identify the dock station and navigate the Mousr robot back to recharge itself.

Our goal is to enable the robot to detect and navigate back to the docking station in a relatively simple environment. Mousr should be able to do this quickly when on low power. We would also like to introduce as little extra cost as possible to the already built system.

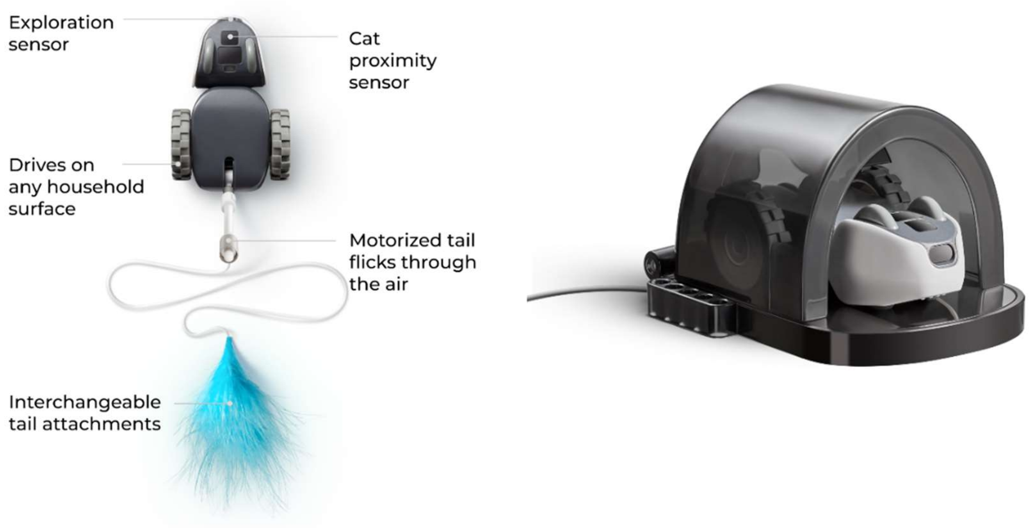

Figure 1. Mousr Overview and Current Charging Dock

Background:

A variety of self-docking commercial robots currently available in the market. Cleaning robots like Roomba and iRobot are the most recognizable. They all use multiple hardware sensors and computational-heavy algorithm to map and navigate through the room. Some newer robots even utilize LiDAR to map the whole 3D environment in order to achieve more precise path planning.

Extravagant environment mapping is not suitable in our case because we need both the size and price to be minute. The sensors we will be adding, and the additional processing unit must be cost-efficient, easy to interface with the already existing software module, and as small as possible.

High-level Requirement List:

“Getting Home Safe”:

- The system must be able to locate and navigate to its charging dock in realistic test environments with a high degree of reliability (85%+ testing success rate) with its battery at a low charge (≈ 5-10% full).

“Load / Unload Compatibility”:

- The charging dock design should allow for reliable entry, secure charging, and easy undocking.

“Timely Processing”:

- The Bluetooth communication scheme, sensor emitter combination, and “Return to Base” algorithm must be able to function cohesively allowing Mousr to process its surroundings and make movement decisions in seconds (5 – 10 seconds).

II. Design

The design scheme our team has developed to achieve the addition of autonomous docking to Mousr’s current specifications involves three main subsections: the sensing hardware, environmental data algorithms, and wireless communication hardware. The sensors serve as an input to the environmental data algorithms, which in turn output navigation commands to the Mousr over Bluetooth Low Energy technology. The sensors consist of 950nm IR emitters, 950nm IR receivers, and a high accuracy Time-of-Flight laser distance calculator. Laser distance data is classified by the “Floor Type” algorithm. IR receiver data is interpreted by the “Return to Dock” algorithm. One BLE module will be fixed onto the Mousr and the other will be fixed to the dock. The Mousr BLE module will have connections to the dock, and the internal system of the Mousr.

Block Diagram:

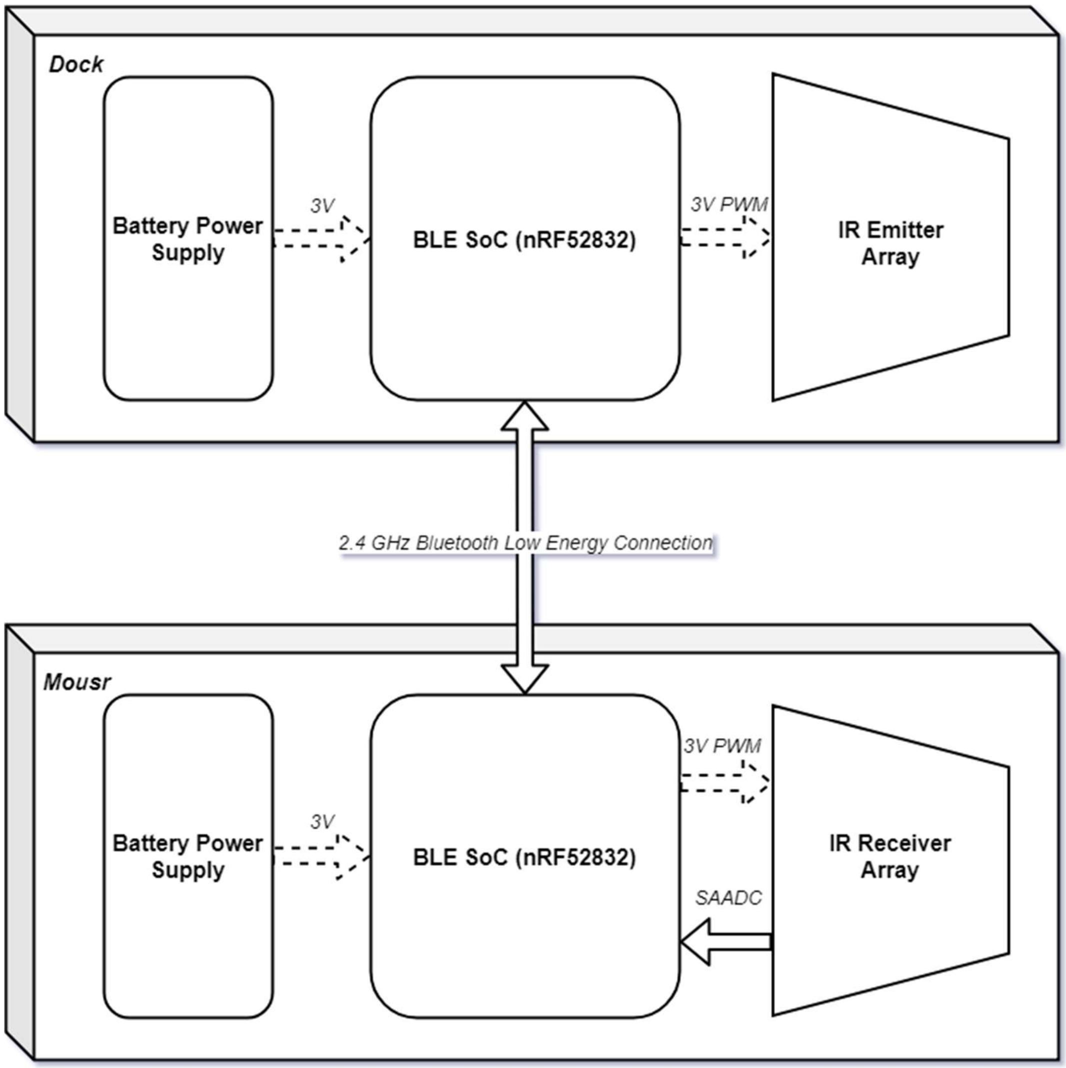

Figure 2. Communication with Dock and Robot

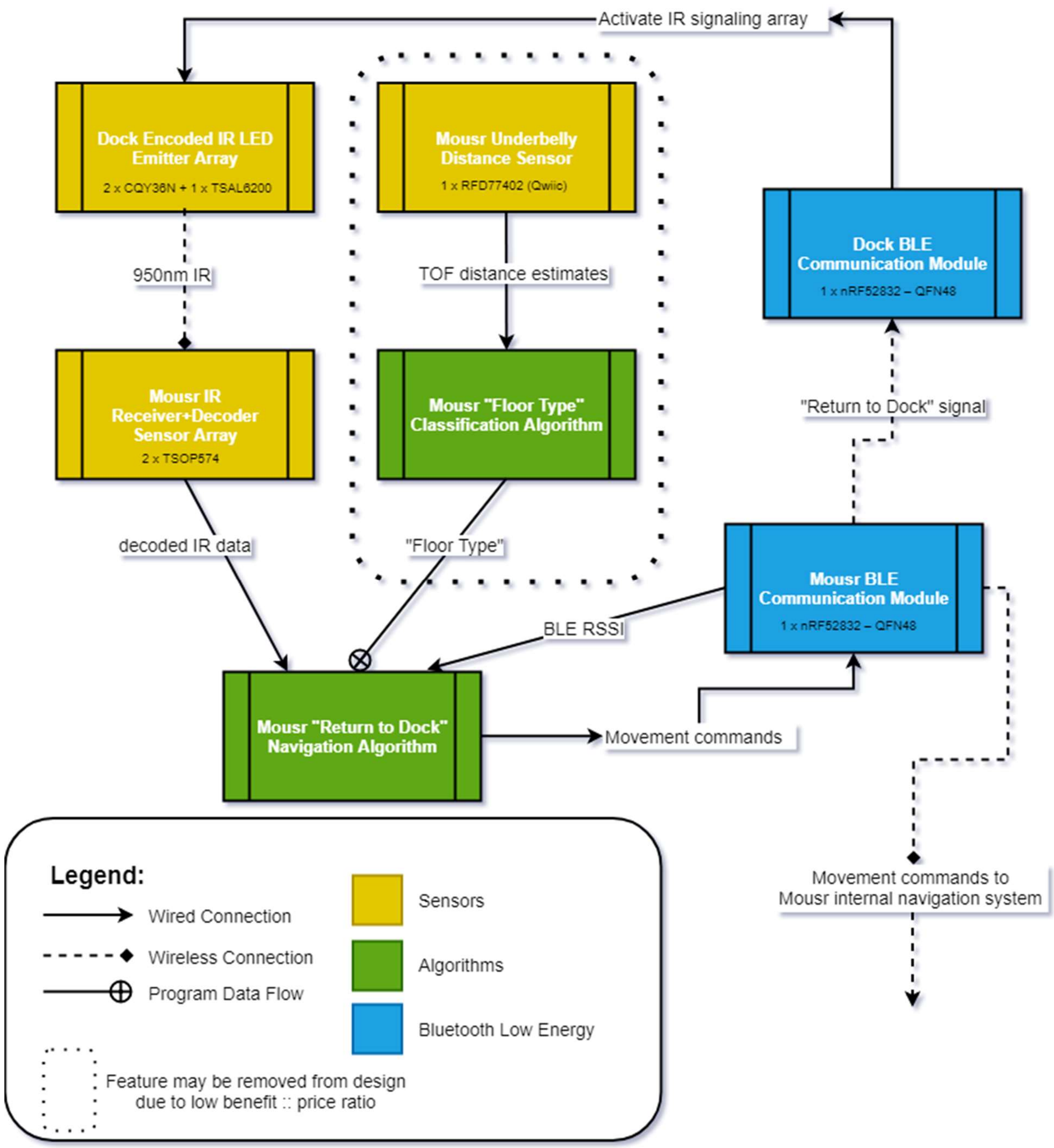

Figure 3. Block Diagram

Functional Overview:

II – 1 Charging Dock Sensing

This sub-section handles the transformation of real-world environment measurements to informative and processable data. Sensors were chosen to be affordable, reliable, and to fit the individual design constraints they face.

II – 1.1 Dock Encoded IR LED Emitter Array

The dock's IR LED array will consist of 3 directionally pointing 950nm emitters (2 x CQY36N @ ≈ $1 + 1 x TSAL6200 @ ≈ $1)[8][12]. Each LED will be emitting a different code, and all will be encoded using the same method (encoding method TBD). The dock's LEDs from left to right will be referred to as "Left Net", "Center Spear", and "Right Net". Their names are referring to their shape and signaling technique (see Figure 4. below in Physical Design section). Their purpose is to signal the Mousr's receivers to facilitate a return to dock when Mousr indicates it is low on battery or idle.

Requirements	Verification
Must be able to transmit encoded IR @ 950nm that receiver can detect and decode in realistic indoor environments with a range > 3 meters.	A. Output IR receiver's received intensity in a lab test taking measurements to determine the upper and lower bounds of intensity range. B. Once the range of the emitter has been established, lab tests within the newly defined distance bounds can confirm that the emitter is able to transmit the encoded signal correctly

II – 1.2 Mousr IR Receiver + Decoder Sensor Array

The Mousr's IR decoder array will consist of 2 directionally aligned 950nm IR receivers (2 x TSOP574 @ ≈ $1)[13]. One will face left, the other right. These will be the most crucial element of Mousr's "Return to Dock" strategy. Their purpose is to help Mousr figure out where it is located in relation to the dock. Their data will be used continuously to make real time decisions during the Mousr's "Return to Dock" procedure. The processor onboard the connected Nordic BLE chip will decode and interpret the signals.

Requirements	Verification
Must be able to decode IR @ 950nm signal in less than 1s and not misinterpret household IR noise	A. Feed receiver array with targeted IR signal frequencies B. Pull out decoded data and time elapsed C. Compare the results with the correct value and time spent D. Retest transmission with IR noise in room

II – 1.3 Mousr Underbelly Distance Sensor

A Time of Flight laser distance sensor bounces light off a target and measures the elapsed time to determine distance. The RFD77402 (Qwiic breakout) provides millimeter accuracy in an ideal range of 100mm – 2000mm [9]. This is compatible with the clearance under the Mousr and can be used to take a burst of measurements of the distance from the toy to the ground. This data is processed by the "Floor Type" classification algorithm which is trained to detect how data from common *flat* surfaces (wood, metal, rubber, cement) deviate from common *rougher* surfaces (carpet, tile).

Requirements	Verification
Must be able to take a burst (7-15) of mm-accuracy distance measurements within 10ms	A. Fix sensor to stable surface B. Compare physically measured distance to sensor measured distance (in mm) C. See how many measurements can be taken in a second and divide to get number per ms

II – 2 Environment Data Algorithms

This sub-section is fundamental to solving the problems and obstacles associated with autonomous docking. It processes the data output from the sensor arrays to provide movement commands to be sent wirelessly to the Mousr. The strategies we use to get Mousr to locate and navigate to its dock are based upon use-space assumptions, and our physical design/sensor layout.

II – 2.1 Mousr "Floor Type" Classification Algorithm

The current floor type Mousr is on can help it make decisions if it knows the floor type the dock is on. This algorithm could be trained to detect if a burst of measurements from the underbelly sensor represent a flat (wood) or rough (shag carpet) surface. It gives its output to the "Return to Dock" algorithm. If the measurements are too noisy due to the Mousr being airborne for example, this system should output "Too Noisy" to alert the "Return to Dock" algorithm that the current data is not useable.

Requirements	Verification
Must return whether surface is "Rough", "Smooth" or "Too Noisy" in under 5000ms with moderate accuracy (65%+)	A. Test sensor and algorithm on a multitude of flat and rough surfaces to ensure correct classification B. Test a variety of noisy measurements to simulate Mousr's unpredictable state during usage C. Use data from tests to compile accuracy and speed requirement validation

II – 2.2 Mousr "Return to Dock" Navigation Algorithm

This algorithm is the central logic behind the Mousr's ability to locate and navigate to its dock. When Mousr is in range of the dock's IR signal, data from the bi-directional IR decoder array (left, right) tell the Mousr its orientation relative to the dock. Based on what code the receivers are getting (Left Net, Center Spear etc. see Figure 4) the algorithm will decide how Mousr should move next. When Mousr is out of range or obstructed from the dock's IR it can improve the robustness of its decision-making process by taking into account the current floor type from "Floor Type" classification, and BLE Received Signal Strength Indication (RSSI) from its connection to the dock (accurate to around 2m in some indoor scenarios)[11]. This algorithm outputs the current movement instructions to be delivered to the internal Mousr system over wireless BLE.

Requirements	Verification
Must be able to output the correct commands to navigate Mousr to dock when in receiving range with a high degree of reliability (85%+ success rate in testing).	A. Run a series of lab tests and confirm that algorithm is outputting the correct movement command based upon forced IR inputs B. Run tests simulating actual returns to charging dock C. Compile data from test to establish success rate in ideal conditions

II – 3 Wireless Communications

This sub-section is responsible for interfacing with the current Mousr specifications and keeping all aspects of the design in synchronization. Bluetooth Low Energy technology is to be used for communication between with dock, the external autonomous docking system on the Mousr, and the internal Mousr navigation system.

II – 3.1 Dock BLE Communication Module

This module uses one Nordic Semiconductor nRF52832 (QFN48) BLE hardware to communicate with Mousr. Gets sent “Returning to Dock” signal from Mousr to activate IR LED emitters. (nRF52xx chosen by Petronics) [10]

Requirements	Verification
Must be able to successfully establish a line of wireless communication between the dock and the Mousr indoors at up to 8m	A. Pair the Mousr robot with the dock station and send data packages to the dock B. Move the robot 0.5m further from the dock each time to see when will the dock stop receiving the data package

	C. Determine the maximum range of transmission from the robot to the dock

II – 3.2 Mousr BLE Communication Module

This module uses one Nordic Semiconductor nRF52832 (QFN48) BLE hardware to communicate with the dock and the Mousr internal system. It sends the movement command output from the "Return to Dock" algorithm to the Mousr internals. It also should notify the dock when its low on battery. It supplies the RSSI value to estimate distance to the "Return to Dock" algorithm.

Requirements	Verification
Must be able to successfully communicate with charging dock and Mousr internals indoors at up to 8m	A. Put the Mousr robot at 5-10 distinctive locations within the room B. Fix the charging station's position C. Try sending command that switch the IR sensor ON and OFF to the station see if the station reacts.

Physical Design:

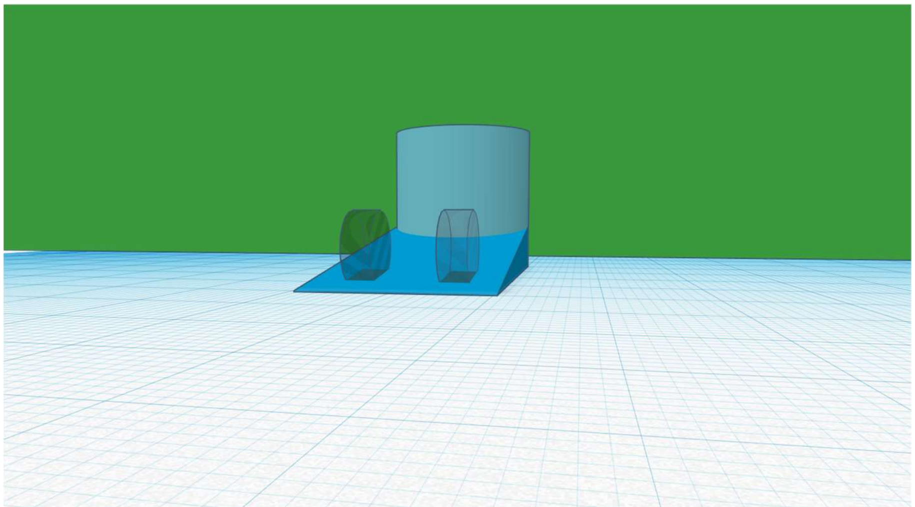

Figure 4. 3D concept for improved Mousr charging dock, designed for autonomous docking compatibility. Low incline ramp. Wheel wells for secure fit. Rounded face for radial IR spreads.

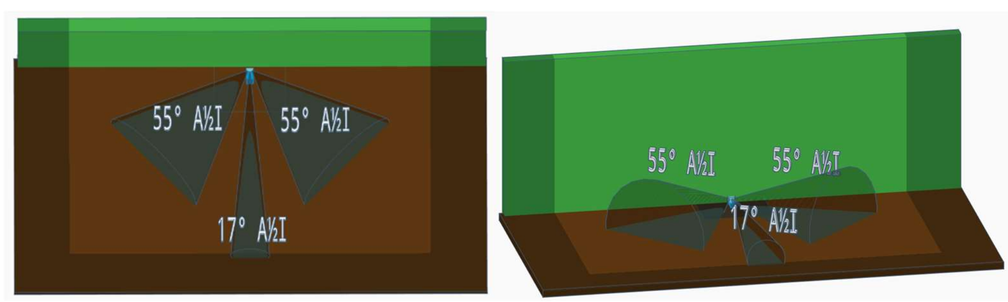

Figure 5. IR emitter array field layout: Left Net, Center Spear, Right Net (A½I = angle of half intensity)

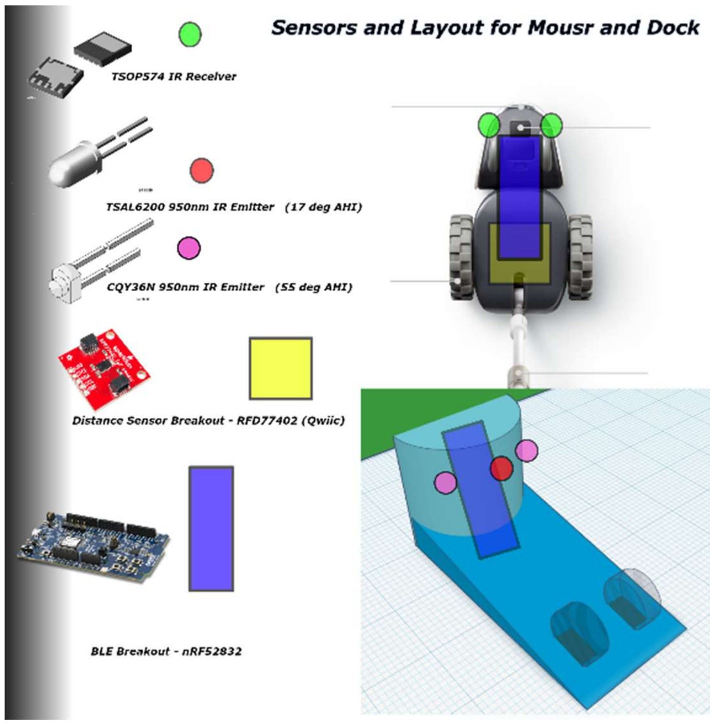

Figure 6. Prototype Hardware Layout

Schematics

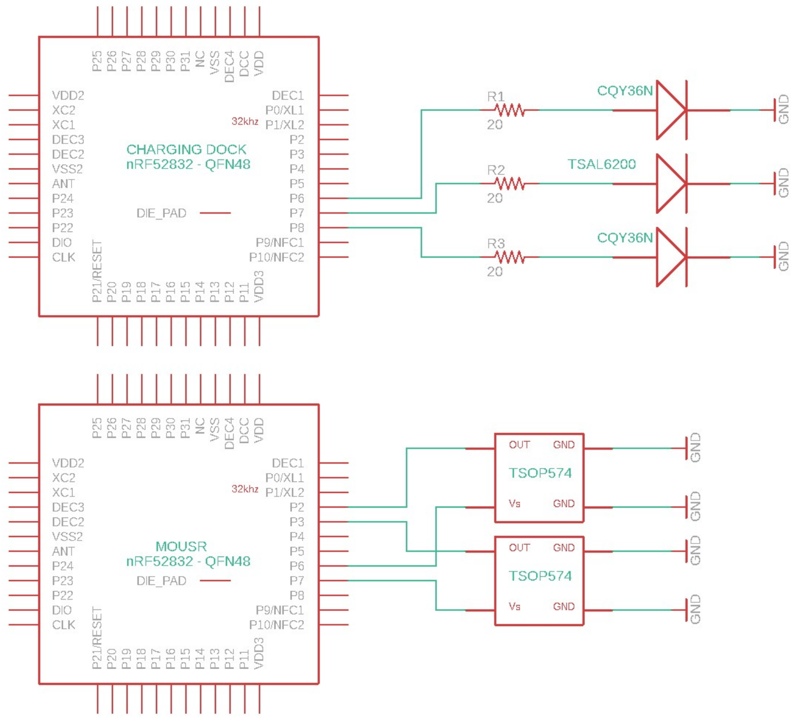

Fig 7. Extra components schematics (excluding recommended layout part)

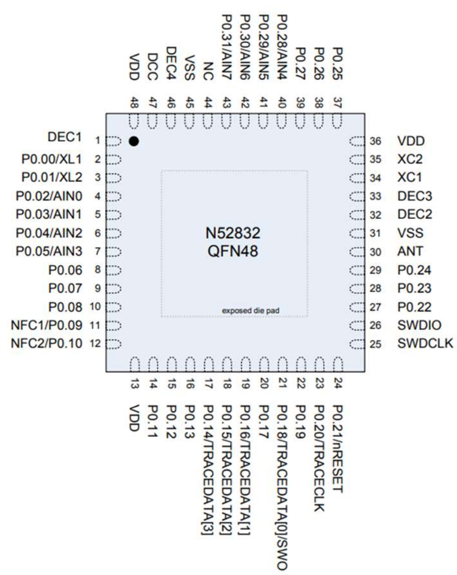

Fig 8. NRF52832 Chip package information

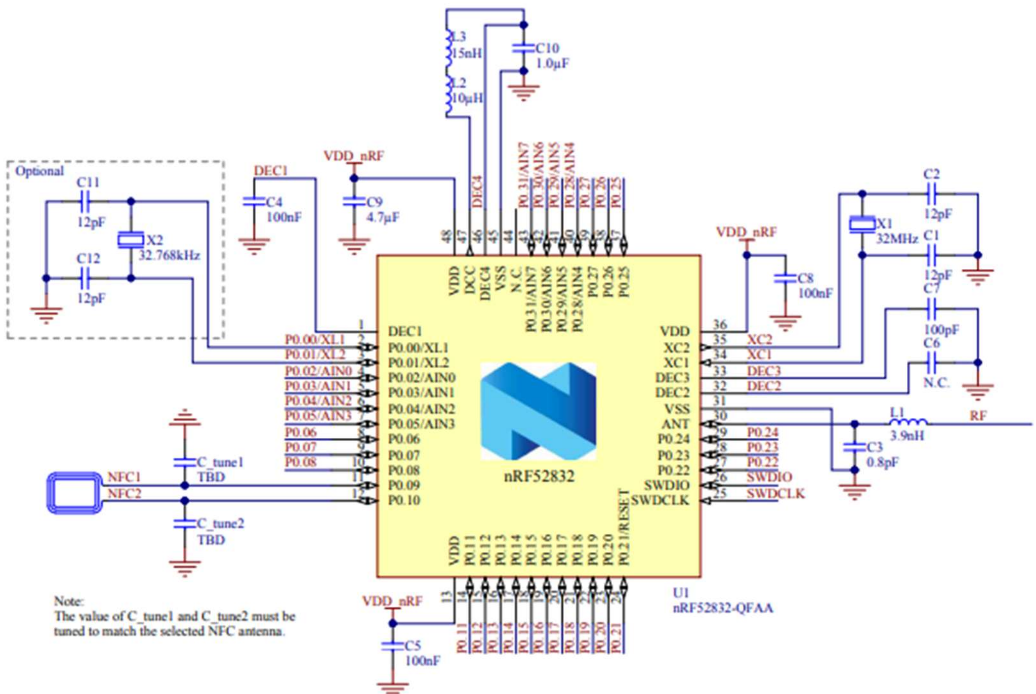

Fig 9. NRF52832 recommended layout

Software

The software can be divided into several functional blocks, as shown in the figure below.

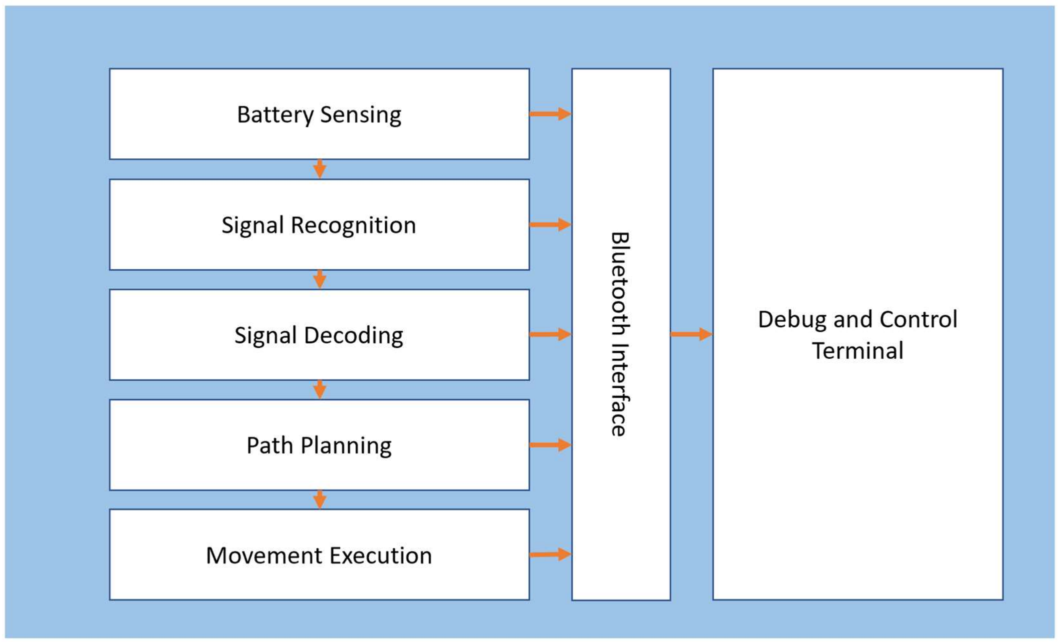

Figure 10. Block Diagram

The battery sensing block is mainly used to sense the battery level, we are thinking of using an event listener type of mechanism to listen to the battery level low interrupt sent to the system.

Signal recognition block and signal decoding block are used to first detect if there is IR signal present in the current setting and to decode the signal, confirming the direction the robot should be facing.

Path planning block is the main block to determine where the robot is currently at, utilizing all sensor mechanism we have on hand, such as proximity sensor, IR sensor, and Bluetooth RSSI value.

And then the movement execution block communicates with the firmware level of the original system to initiate the movement according to the path.

Finally, we add a debug layer so that we can monitor the current status of the robot and sending commands to the robot.

Tolerance Analysis

The main risk present is how accurate can the robot identify the target signal[4]. We all know that many appliances have some inherit infrared signals, such as remote controls and fridges. So, to be able to distinguish between the target signal and the “noise” signal is one challenge, we may need to encode the infrared signal so that when the robot senses a typical pattern of infrared signal, it will decode and recognize it as the target to go to.

Another important tolerance is the Mousr’s ability to emit and detect the signal. The components we are using emits the IR signal in three fields, one narrow middle field (the IR ‘spear’) and two wider fields to the left and right of the middle field (the side IR ‘nets’). The component for the IR spear, a TSAL6200 high power 940nm IR emitting diode, has an angle of half intensity of ±17° (the point angle where the intensity of the signal is half from maximum) while the IR nets, each of them a CQY36N high power 940/950nm IR emitting diode, has an angle of half intensity of ±55°. Outside of these fields, the ability for the Mousr to detect the signal is significantly reduced as the intensity has dropped below half its intensity from initial propagation.

The two IR Receivers, which are of the model TSOP 574xx, each has an angle of half sensitivity of ±75°. The total angle of half sensitivity in degrees is at minimum ±150° if they don’t overlap the fields where the sensitivity is above half the maximum. This in turn is wide enough to capture the majority of the emitted IR from the diodes as the minimum total angle of half intensity without overlap of above half intensity fields is ±127°. These receivers should be able to receive IR signals with a minimum of Radiant Intensity of .75 Milliwatts per Steradian, half the Radiant Intensity of the Side IR nets; while at maximum be able to read an IR signal with a Radiant Intensity of 72 Milliwatts per Steradian, the Radiant Intensity of the IR spear. The datasheet for the TSOP 574xx component also states that the data signal received should be close to the device’s band-pass center frequency (which is either 36, 38, 40, or 56 kHz). Sources of noise that are suppressed include DC light (such as tungsten bulbs and sunlight), continuous signals, and both 2.4 GHz and 5 GHz wifi signals. The TSOP 574xx also suppresses complex and critical disturbance patterns such as infrared from a fluorescent lamp with high modulation or highly dimmed LCDs.

The angle of half sensitivity approximates a cone of view where how far a signal can be detected also depends on how far off from the normal axis the signal is being received from.

For the receiver's angle of half intensity of ±75° when the IR signal is 1 foot to the left of normal axis (or is at a height of 1 foot):

1*tan(±75°)=3.732, which means that the minimal distance along the incident axis to detect the signal is 3.732 feet. Within this minimal distance the cone will not capture the signal.

Meanwhile, for a signal that is 5 feet to the left/right of normal axis or at a height of 5 feet:

5*tan(±75°)=5*3.732=18.660, which means that the minimal distance along the normal axis to detect the signal is 18.66 feet.

Another important thing to take into consideration is the Spectral Sensitivity of the sensor. Signals with a wavelength too short or too long will be mostly ignored by the sensor. As shown in Figure 10 from the TSOP572 datasheet [13], the range in where the sensitivity is roughly at or more than half of maximum is between 850 nanometers and 1075 nanometers

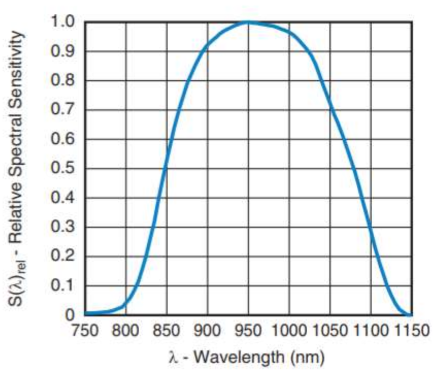

Fig. 10 - Relative Spectral Sensitivity vs. Wavelength

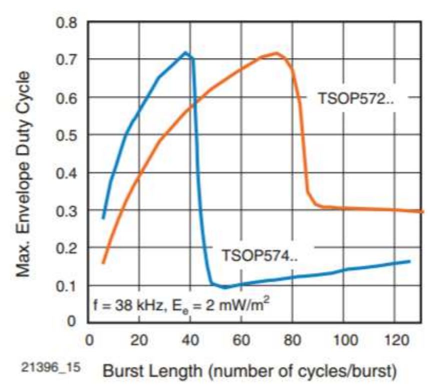

Fig. 8 - Max. Envelope Duty Cycle vs. Burst Length

The sensors also filter out signals based on other factors such as burst length. For TSOP572, signals will start being filtered out if their Burst Length exceeds about 85 cycles per burst as shown in Figure 8 of the datasheet [13] wherein the Max Envelope Duty Cycle drastically drops off at around that point.

III. Costs

Based on the fact shown on ECE Illinois website[14], we calculated an estimate hourly salary of $38/hour. We expect to work 10 hours per week for each member in the group, and we consider 90% of the work during the 13-week-long project, except our regular meetings with Petronics.

$$3 \times \frac{\$38}{hr} \times \frac{10hrs}{week} \times \frac{13weeks}{0.9} = \$16467$$

Hardware Cost for Prototyping

For prototyping we are to use more parts than what a single unit might need during production for the following reasons. First, this can serve as a failsafe in case of any accidents such as receiving defects and soldering failure. Second, it saves time in case we might need to order more than once. And the total estimated cost is $206.14.

Parts	**Part No.**	**Unit Cost**	**Number**	**Subtotal**
Bluetooth SoC	nRF52832	$2.83	4	$21.32
Bluetooth Dev Kit	PCA10040	$39	2	$78
IR Transmitter A	CQY36N	$0.468	20	$9.72
IR Transmitter B	TSAL6200	$0.37	20	$7.4
IR Receiver	TSOP57436	$1.47	10	$14.7
Misc. Circuit Components				$5
3D Print Housing				$50
Shipping				$20
Total Cost				**$206.14**

By adding up the expanse for both labor and BOM cost for hardware, we have a total cost of $16673.

Hardware Cost for Production

Parts	Part No.	Unit Cost	Number	Subtotal
Bluetooth SoC	nRF52832	$2.71	2	$5.42
IR Transmitter A	CQY36N	$0.216	2	$0.432
IR Transmitter B	TSAL6200	$0.152	1	$0.152
IR Receiver	TSOP57436	$0.798	2	$1.596
Misc. Circuit Components				$1
Housing			1	$5
Total Cost				**$13.6**

Furthermore, for each piece that will potentially be produced in the future, we have a $13.6 BOM cost introduced into the already existed BOM cost.

IV. Schedule

No.	Week	Robert	Yuhao	Justin
1	2/4/2019	Project proposal	Project proposal	Project proposal
2	2/11/2019	Contact with Petronics	Gather List of material	
3	2/18/2019	Design Documentation	Design Documentation	Design Documentation

4	2/25/2019	Schematics refine and get familiar with the SDK	Get familiar with the SDK and PCB layout	PCB layout
5	3/4/2019	PCB final check, Software environment setup	Software environment setup, research on how IR behaves	Software environment setup
6	3/11/2019	Model the dock	Test version 1 software	Test version 1 software
7	3/18/2019	3D printing the dock design	Modify software	Revise PCB design
8	3/25/2019	Test software version 2	Test software version 2	Revise PCB design
9	4/1/2019	Integration of hardware and software platform	Integration of hardware and software platform	Integration of hardware and software platform
10	4/8/2019	Test software version 3	Test software version 3	Feedback on unmet requirements
11	4/15/2019	Final integration	Final integration	Final integration
12	4/22/2019	Prepare presentation and final software test	Prepare presentation and final software test	Prepare presentation and final software test
13	4/29/2019	Final presentation and report	Final presentation and report	Final presentation and report

V. Safety and Ethics

There are several safety and ethics issues that are relevant to our project. Pertaining to point #1 of the IEEE Code of Ethics [4], we must ensure that the materials we use to build the Mousr is non-toxic to pets, as cats tend to hold things in their mouths and such the cat may accidentally ingest the material. A thing that must also be taken into consideration is the product's impact on the environment, whether the materials it is made of can be potential pollutants such as the outer shell and battery.

According to the user guide for Mousr [5], the device uses a lithium-ion polymer battery which contains hazardous materials. To avoid harm, the battery must not be overcharged and must not be exposed to extreme temperatures. The battery must also not be left to charge overnight because of issues that can be caused from overcharging. We should figure out a way to program the device so that it becomes active and leaves the charging station when it has detected that it is at full battery.

The sensor of the Mousr could also pose a potential privacy issue to the end-user. We must ensure that the data that the Mousr collects in order to navigate will not be used for malicious means, such as making sure the data cannot be transmitted from the device and that it cannot be used by third parties.

According to OSHA safety standards for robots, we must also account for safety issues that can possibly be caused by the electrical system [6]. Exposed wiring can be potentially dangerous as even a low voltage wire can be dangerous. A similar concern would be making sure that there aren't exposed moving parts that can cause potential harm to any users (such as gears catching hair). To ensure the user's safety we must make sure that the outer shell of the Mousr doesn't expose any of these moving parts or electrics.

VI. References

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