University of Tennessee
Knoxville

Final Report

Team #1

MKart
Min Kao Autonomous Robot Tour

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Customer:
Dr. Mark Dean

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Executive Summary

Our group was tasked with the design, construction, and implementation of a fully autonomous robot that would be able to navigate a route in our department building, Min Kao, and provide an audio tour pointing out a few interesting points and details. This Min Kao autonomous robot tour, MKart for short, is for our customer Dr. Mark Dean from the University of Tennessee's Department of Electrical Engineering and Computer Science as our Senior Design project. This tour is effectively the start of what will likely be a series of projects with increasingly ambitious design goals that build on the functionality and products of previous groups. In this regard, it was important to us that we experimented with a variety of solutions and components to help build a base understanding of what elements will work best for an autonomous tour.

The design of our project had to deal with two major design problems, how to navigate a building effectively and how to avoid random use cases such as obstacle avoidance. Early on, a decision was made to contain our project design within the device itself. The means avoiding the use of any sort of external communications or beaconing technology to address the issues. This would prove to be a significant choice, as our research showed that very few effective techniques had been developed for spatial awareness in a mobile robot, even less on a budget. As we would discover, finding a solution to this problem would be time consuming, and would require a flexible approaching where methods had to be dropped upon realization that they would not be feasible for our requirements. The object avoidance was less of a direct issue, but more of an iterative process which required constant updating. With a simple and effective hardware portion, object avoidance as well as path navigation, came down to a complicated software integration process that would have to consider a vast array of use cases and prioritize multiple data streams. These two aspects of our project would consume most of our time and resources but would also prove to be the most rewarding to realize.

Considering the scope of the MKart, it became clear a traditional approach to design would not be very time conscientious. Although our research was significant, we decided to dive into hardware and software testing early on. This was aided by the fact that the original robot kit was provided by our customer at the onset. Seeing as how we were exploring fairly new territory and experimental designs, it was important that we gave ourselves plenty of time to try solutions and be prepared to change fundamental approaches if needed. This process would realize itself many times throughout the semester, but perhaps most definitively when we had to change the process by which we navigated the building and determined spatial positioning just after the middle of the semester. This methodology would also affect how our team had to work together. A mix of electrical engineers and computer scientist in our group encouraged a division of labor, but at the same time very little could be accomplished without near constant communication and collaboration. The MKart is essentially a complex embedded system that required many layers of abstractive integrations, and working on the line between hardware and software was consistent

aspect of the process. Inevitably, many team members found themselves learning about and working in new engineering spaces they had not envisioned early on.

The culmination of a final tour has still not yet been achieved at the writing of this report. Despite this, we have been able to navigate the entire tour path. Achieving this milestone was a truly rewarding experience, but there is still work yet to be done. The final tour is expected to take approximately 10 minutes, and explores two floors of Min Kao, the Electrical Engineering and Computer Science department building. We will start in the atrium where senior design presentations are taking place, and follow a path up to the fourth floor atrium pointing out and entering a senior design lab, showing multiple offices including Dr. Dean's office, and providing information about the department and college. Given loose guidelines for the content of the tour, the script and recordings for the tour were largely done at our discretion. It was important to us that we provided an accurate and informative tour, but the correct operation and proof of concept of the technology was inherently a greater priority. As such, the tour audio has been left as the last stage of the integration.

An important theme of the project has been documentation. This aspect of engineering and design is undoubtedly understated. Much of the original tech we started with came with little or very poor documentation, and a large portion of our time was spent deciphering the operations of the board sets and components because of this. Conversely, correctly and extensively documenting our design, such as pin mappings and schematics, would prove to be immensely beneficial when having to make major redesigns. As we approach the conclusion of our project, it is our hope that these reports along with the rest of our documentation will help provide a good platform by which other groups can build. We were faced with many obstacles and difficulties that arose in all aspects of our design, but the process of having to continually redesign and experiment to reach our design goals would prove to be an invaluable learning experience which we explain in detail here. The ability to learn and build on other's mistakes and successes is the bedrock of the engineering process, and we hope our contribution through MKart will prove to be a valuable start to future autonomous robot designs.

Requirements

1. Path Route and Programming
    1.1. The robot must follow a designated path through Min Kao.
    1.2. The robot must tour at least two different floors in Min Kao.
    1.3. The robot must enter and exit two designated rooms along the path.
    1.4. The robot must enter and exit an elevator to change floors.
    1.5. The robot must be able to relocate the path if its trajectory diverges.
    1.6. The robot must stay close to the center of the hallway.
    1.7. The robot must move at a reasonable, consistent speed for touring.

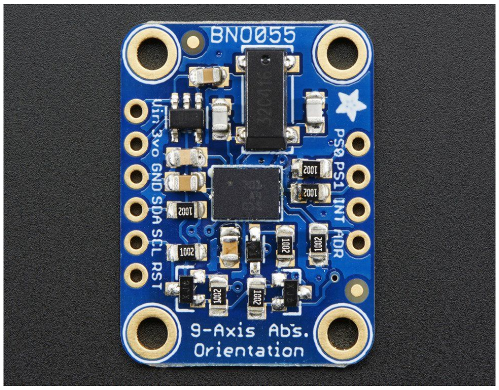
2. Location Detection
    2.1. The robot must know its current position.
    2.2. The robot must report it if it encounters a problem and cancel the tour.
    2.3. The robot must be able to determine what floor it is currently on when using the elevator to avoid getting off on the wrong floor.
3. Object Avoidance
    3.1. The robot must avoid sudden dropoffs such as stairs.
    3.2. The robot must avoid elevator doors and room doors until they are open.
    3.3. The robot must avoid people walking in its path.
    3.4. The robot must move around obstacles in its way if possible.
    3.5. The robot must stop and ask for assistance if there is no possible path around an obstacle.
    3.6. The robot must not run into anything.
4. Audio Output
    4.1. The robot must play audio clips for the tour based on its current location.
    4.2. The robot's audio must be loud enough to be heard by a tour of 20 people.
    4.3. The robot must ask for assistance to call an elevator.
    4.4. The robot must ask for assistance to open and close doors.
    4.5. The robot must report if it encounters a problem during the tour.
5. Design
    5.1. The robot's design must not present any hazards or dangers.
    5.2. The robot must be dutifully designed with some regard for appearances.
    5.3. The robot must be able to withstand minor collisions and drops with reasonable durability.
    5.4. The robot must include a flag or object to visually signal its location.

Changelog

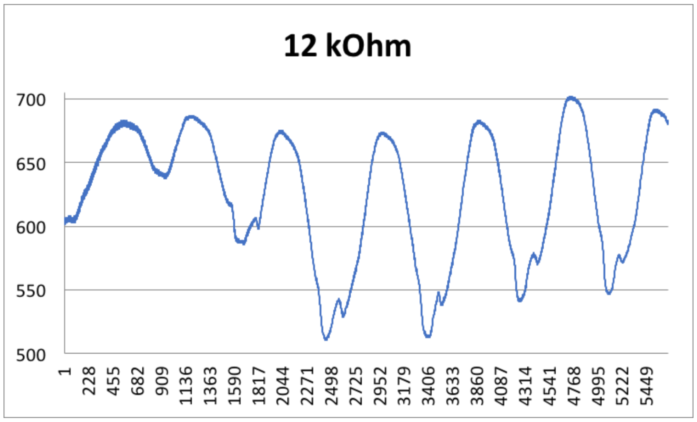
1. Path Route and Programming
    1. 5. The robots must be able to make minor adjustments to avoid obstacles around the path
2. Location Detection
    2.1. The robot must know its current location on the path.
3. Object Avoidance
    No Changes
4. Audio Output
    No Changes
5. Design
    5.2. Removed

Design Process

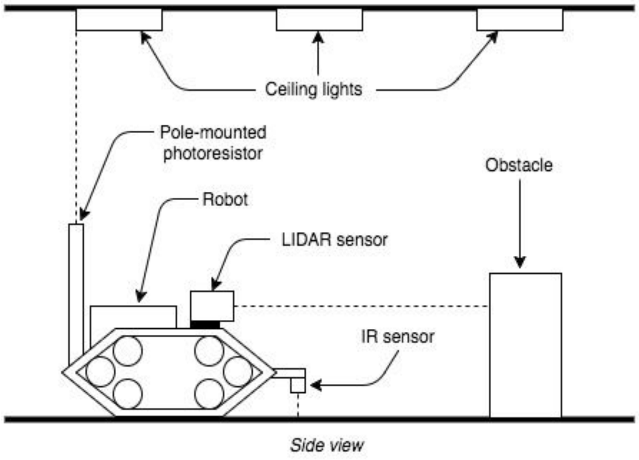
A. Spatial Awareness Solutions and Implementations



Our first issue to address was spatial awareness. We briefly explored the possibility of using localized GPS, but it became clear that this solution would be far too expensive to stay within our budget. Also, we had made the decision to try and contain all aspects of the design to the robot chassis itself, so as not to depend on external beaconing methods. The next item we explored was an IMU, or inertial measurement unit. Pictured to the right, an IMU combines an accelerometer, magnetometer, and gyroscope along with a microcontroller to determine 3D spatial orientation. With most of the algorithms contained within the chip set, it is capable of outputting absolute orientation, angular velocity vector, linear acceleration vector among other data. This seemed like an ideal solution for our purposes, and a good portion of the semester was spent trying to determine how to utilize it. Unfortunately, the accuracy offered by the IMU was not effective enough for our requirements. Our primary use would be to determine a displacement vector from the acceleration vector to realize the distance we have traveled. This required a double integration, which we had to do using Riemann sums, a complicated mathematical process which leaves much to desire both in terms of efficiency and accuracy. The primary issues arose when we realized the IMU always had a slight, varying offset in the acceleration vector that when integrated down twice would produce huge, compounding errors in displacement. When the IMU was proved to be orders of magnitude less accurate than simple timing estimates when running the motors, we had to abandon this method and look for a more feasible low-cost solution.



Our second major solution came as a result of research that led us to a couple journal articles about light mapping (Thrun and Burgard). They discuss how a museum tour guide robot utilizes the ceiling to obtain a general understanding of its location. Although we had not considered this originally, we realized it could be an effective solution for our tour as well. Considering we were given a predetermined path, the MKart would only ever need to know its progress down that path. A quick study of the Min Kao ceiling lights shows that they are well-spaced bar lights perpendicular to the hallways. This was ideal as far using lighting as a milestone to determine how far we are progressing down a hall, and what doors and key points are in our immediate environment. A simple photoresistor circuit with a voltage divider would allow us to track lighting changes quite accurately and thus track our spatial progress. Testing on this circuit showed that lighting changes between under the lights and in between them was pronounced. Pictured above is a graph of the varying light (taken as a voltage reading) down a hallway of Min Kao on the third floor that is a part of our tour. By setting thresholds, we can recognize the peaks as bar lights and the valleys as the midpoints in between. The diagram below depicts this process in much more detail. By mounting our resistor on the flagpole of the MKart, we ensure the light diffusion is reduced and our readings are less likely to get obscured or affected by ambient light. One issue with this method is navigating the atrium, which is the end portion of our tour on the fourth floor. We decided to rely on timing and our sensors to navigate this final portion of the tour, but the vast majority of distance covered would be conducive to this "light-mapping" method of navigation.

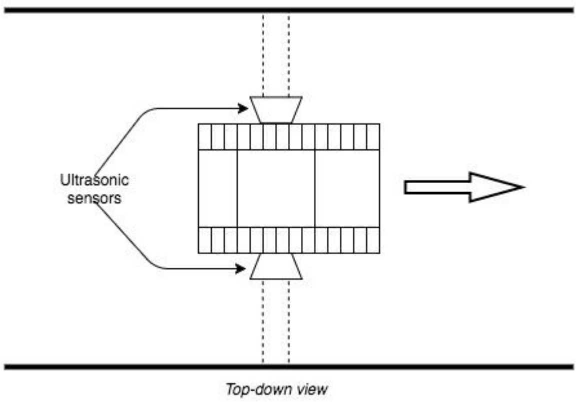


B. Object Avoidance and Navigations Solutions and Implementations

The diagram above also depicts a couple of our sensors that help navigate the immediate environment. This sensor suite was the method we choose to implement our obstacle avoidance and environment navigation techniques. Pictured to the right and below, our sensors consist of a LIDAR sensor, two ultrasonic sensors, an IR sensor, and a BMP180 pressure sensor. The LIDAR, ultrasonics, and IR were all provided by our customer and are responsible for optical sensing. We had discussed many variations on how to utilize and implement these sensors, but we ultimately settled on a hierarchy where the LIDAR would serve as the primary due to its superior accuracy and polling rate. Mounted on a servo at the head of the MKart (as seen in the diagram above), the LIDAR continuously sweeps a wide angle to look for obstacles. After encountering an obstacle, it searches for the best possible routes forward and makes a decision based largely on space available considering both space to move forward and width of each path. This

sensor can also serves as a check against our distance from the walls and entering doorways and elevators based on the MKarts orientation and the servo sweep angle.

The ultrasonic sensors fulfill a secondary protocol that serves as a hallway centering mechanism when used in conjunction with our centering algorithms. Mounted on either side of the robot, the ultrasonics constantly poll the distance to either side, averaging data points due to varying degrees of accuracy. This mechanism was necessary due to very inconsistent motor operations with the provided robot kit. We were encountering drift of varying degrees to either side when all parameters indicated our motors should be driving the MKart straight. By checking the ultrasonics, when can continuously make minor adjustments and correction to our direction to stay close to the center of the hallway. The diagram on the left visualizes this operation.

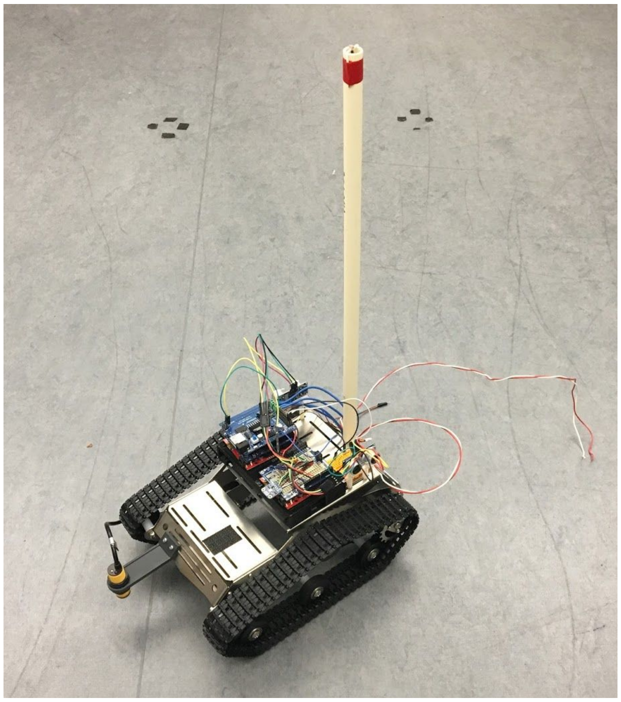


The IR, infrared light, sensor was included simply for edge detection. Although our path does not take us anywhere near stairs, it was important to our customer that we be able to detect drop-offs to avoid catastrophic falls. The IR sensor was a basic binary read-in that would trigger when the sensor detected a distance exceeding a preset amount. As first diagram above shows, we positioned the IR sensor facing down a few inches in front of the MKart on a mount. We also prioritized the sensor as in interrupt, ensuring any operations for navigation or tour would be halted immediately to prevent running off an edge exceeding our mandated height (which was approximately six to eight inches). By mounting the sensor a few inches ahead, we also accounted for any delay and drift forward when stopping.

Our tour takes us up to the fourth floor of Min Kao. Navigation into the elevator would be handled by our optical sensors and light mapping, but we needed a method to determine vertical location to ensure the robot exits on the correct floor. In the scenario that elevator cannot go directly to the fourth floor from the third, but must make other stops, we had to ensure the MKart is able to check and request users bring it to the correct floor. The BMP180 pressure sensor provides this functionality. We can utilize pressure to determine our altitude. By normalizing the readings to initial readings taken on the third floor, we can determine our relative altitude within a half meter. This gives us the accuracy to always know on which floor the robot currently resides. We will only utilize this sensor when on the elevator, checking to see if we are within our relative height thresholds and can progress forward as the doors open.

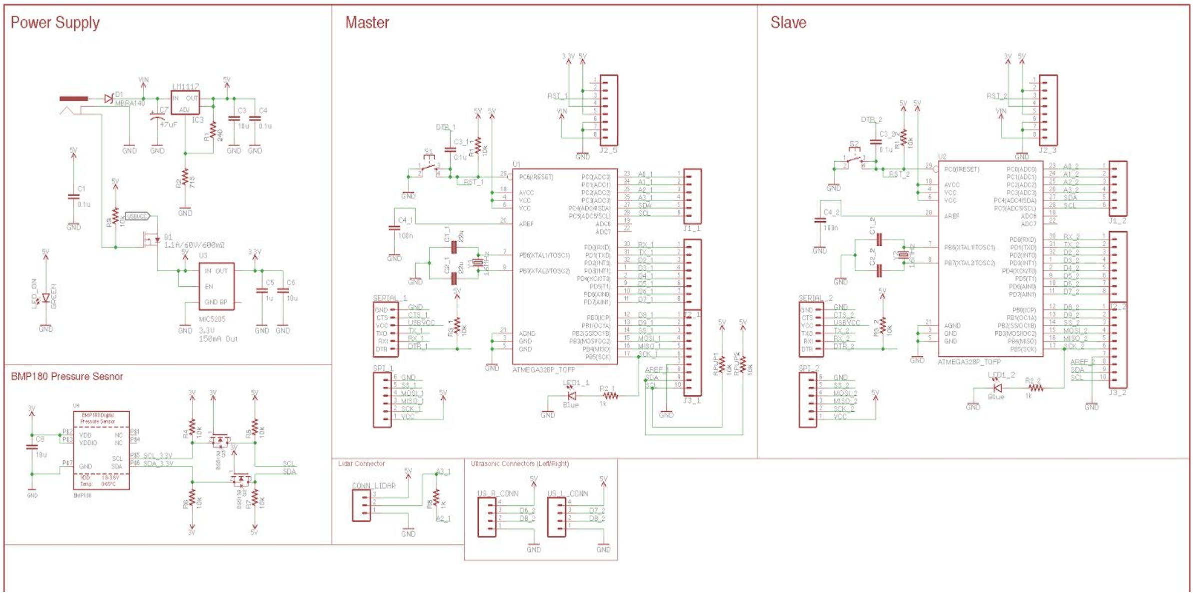
C. Hardware and Software Design Integration

The MKart's hardware evolved continuously as was discussed in the sections above. We made use of the Arduino IDE and Arduino hardware to help integrate our project's hardware and software elements. The general design of the MKart stayed relatively the same, although many of the electrical components would be switched out at various stages. This proved useful as we faced a host of various issues throughout the project's life but could always return to a central hardware design. This design is depicted on the picture below. This early-stage version does not include the LIDAR and mount on the front part of the chassis, but the microcontroller platform is located on the main chassis. The IR sensor can be seen mounted on the front, and the ultrasonics are mounted on standoffs on either side of the main chassis. Lastly, the flagpole is seen here before visual modifications with a working prototype photoresistor circuit at the top.

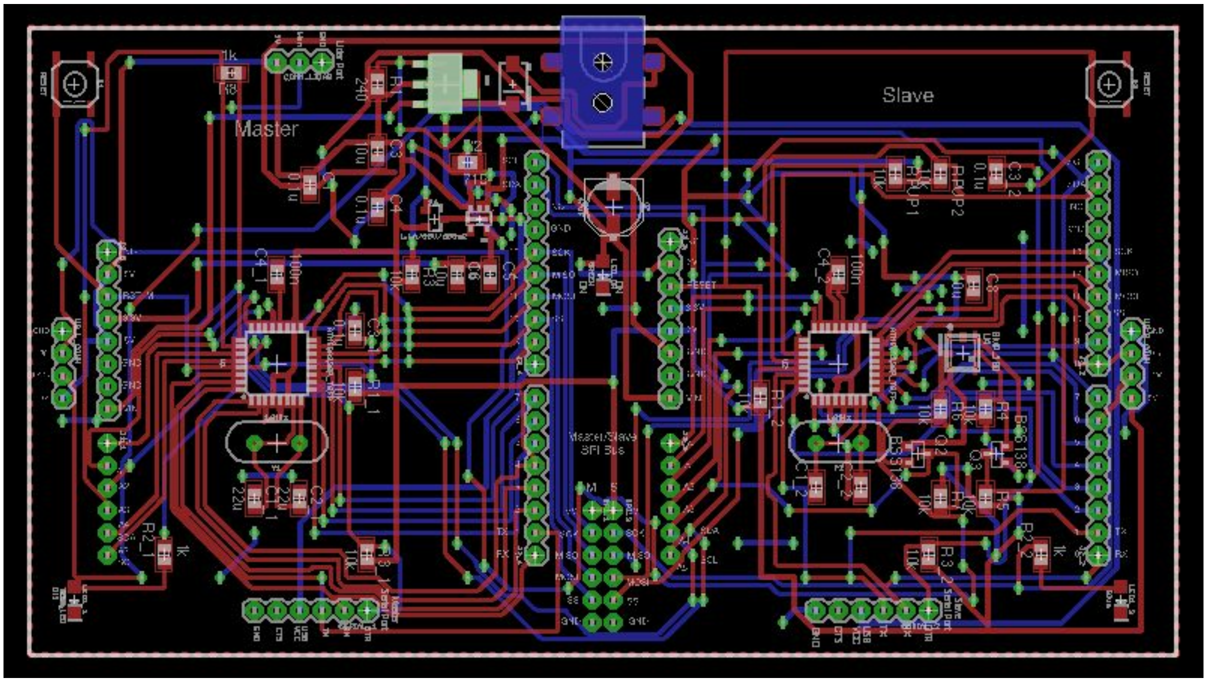


All of the programming was done in Arduino. This was helpful due to the size of the Arduino open-source community. Our original model involved using a combination of two Arduino Unos that would communicate via either the I2C or SPI bus communication protocols. One Uno would handle the ultrasonic readings, pressure sensor data, and the audio wave shield operations (discussed in the next section). The primary UNO would navigate using the LIDAR, motor controller shield, photoresistor circuitry, and IR sensor. We ended up facing many issues with the communication protocols which could never be isolated to a single components or circuitry element.

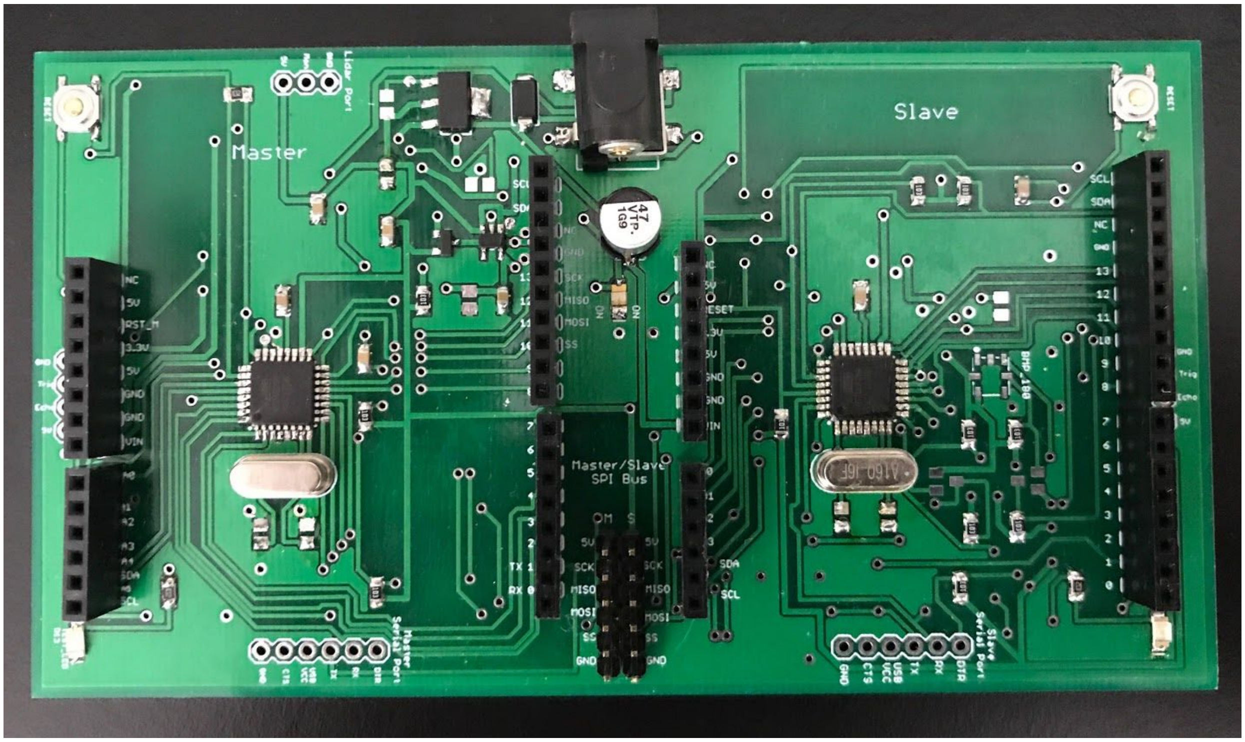
In order to counter the communication protocol issues, we decided to move to our own custom PCB design that would streamline the hardware process and ideally ensure efficacy of operations. This design was completed using Eagle CAD software. Using the Sparkfun RedBoard, a common Arduino Uno clone as an example, our PCB attempted to unify two UNOs onto a single board consolidating power circuitry, communication busses, and breaking out pins specifically for our sensors. This schematic and board layout for the PCB are shown below and on the next page. This board maintained shield compatibility, and we had to ensure the correct pins were accessible so that the microcontrollers could be bootloaded with with compatibility software for the Arduino IDE. After ordering all the correct parts, the PCB was assembled, also shown on the next page. This custom PCB worked for a period of time, but once more we had issues with it intermittently and eventually failing after being hooked up to the full component circuitry. Although we were not able to isolate the issues despite repeated testing of all components, we believe the issue may be sourced at the DC motor controller shield provided with the kit. At the moment of this writing, we are just now investigating new motor control shield which we have better documentation for. We plan to return to either a two Arduino UNO format, or an Arduino MEGA with a sensor shield. A final hardware integration schematic is shown in the following pages.



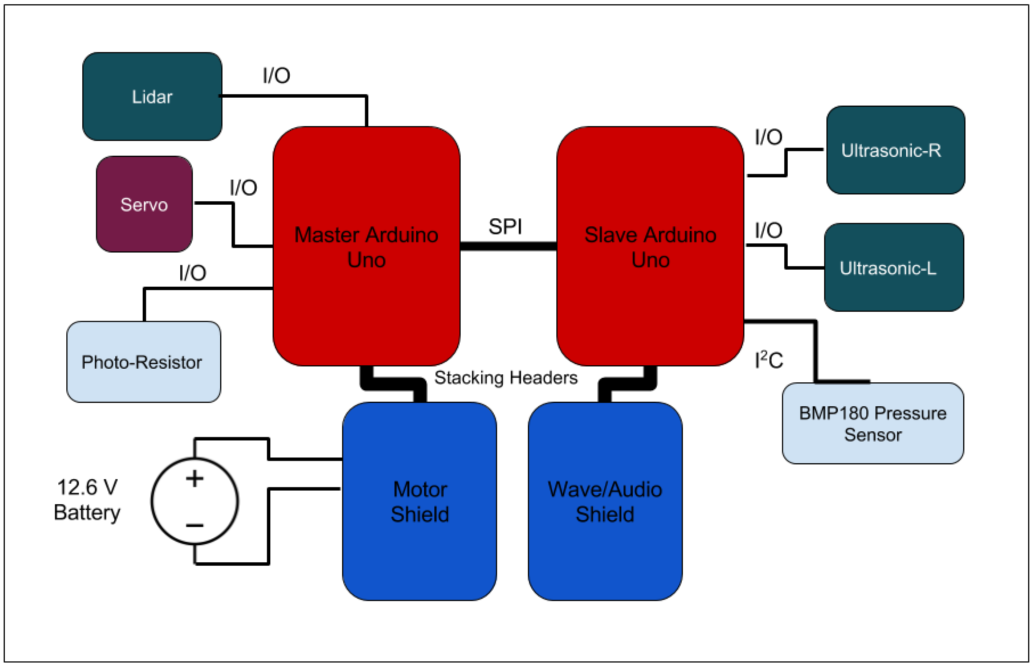
Custom PCB Schematic



Custom PCB Board Layout

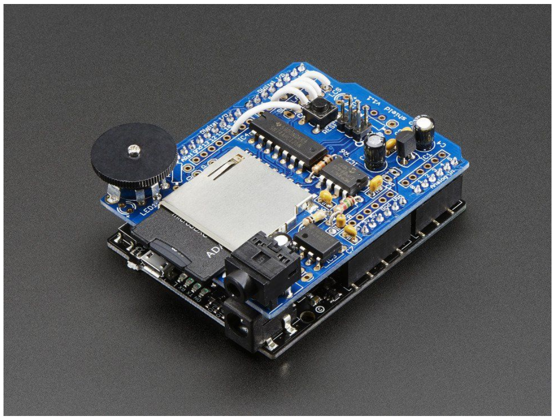


Custom PCB Assembled



Final Hardware Architecture

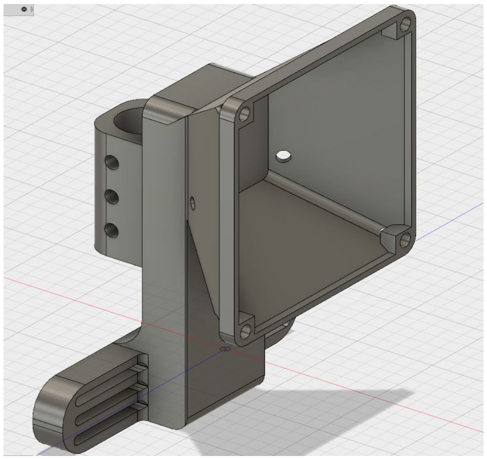
D. Tour Audio Implementation



As stated above, we had quite a bit of freedom with regards to the content of the tour. We ensured we met our customer's requirements and focused on keeping the tour short but informative. Our script was written by our team and recorded using a USB microphone setup. In order to play audio at the corresponding parts of the tour, our research brought us to the Adafruit Wave Shield, pictured to the right. This shield handles much of the signal processing and analog to digital conversions required for converting and playing audio files. Using the on-board SD card holder, we are then able to store and request specific audio files as needed throughout the tour. This shield utilizes the SPI bus when communicating with the SD card, so much time was spent debugging this communication protocol and ensuring bus contention would not be an issue. Additionally, the speakers we bought to be driven by this shield were not very loud. In order to remedy this issue, we are considering including a separate battery powered speaker which will plug into the shield via the 3 mm auxiliary cable output.

E. Additional Design Considerations

The MKart proved to be a challenging design process that would test the bounds of our knowledge and require us to explore new areas of interest and research. For example, we needed to ensure that our robot was able to communicate with its environment effectively. That is why our tour audio includes snippets that may ask assistance in moving obstacles, opening doors and elevators, and ensuring we reach the correct floor. Also, we needed to consider the possibility of someone accidentally stepping on or not noticing the robot in case they are unable to hear the tour audio or motors. For this reason, we included the flagpole to provide a visual aid at a more reasonable height. Many of our hardware components had to be 3D printed, as our custom designs and circuitry could not be mounted easily otherwise. One of these mounts is depicted on the left. This part holds our speaker and pole to the back of the robot chassis with a screw locking plate. We also had to be flexible with our circuitry as many components had to be replaced or redesigned throughout the semester. Large portions of the



front chassis were left open in case we ever need to use breadboards to test specific circuits and components without permanently soldering or wiring them in. The importance of keeping a flexible yet well defined design inevitably proved useful as we had to troubleshoot at all stages of the MKart's design.

Lessons Learned

A. Issues Encountered

Throughout the project, there were many problems we faced that were tough to solve but will serve as great lessons for our future projects. The first issue was that the two 12v dc motors that came attached to the chassis from our kit receive slightly different signals. Due to this, the robot would not drive straight when each motor was given the same speed values through pulse width modulation, which caused the robot to drift off to the left or right, and eventually run into a wall. To combat this, we adjust the speed values given to each motor to match the actual motor speeds to be as close as possible. Another similar and related issue we encountered is that as the battery powering the motors and arduino ran out of charge, the speed of the motors would change nonlinearly. To reduce the effects caused by this, we have tried to keep the battery charged fully for most testing; however, for both these issues, we opted to use the ultrasonic sensors primarily to correct for drift and help the robot move back to center of the hallway. In addition, we will sweep the lidar sensor 180° to get an accurate reading of where the robot is in relation to the walls on either side.

Two more major issues we identified were associated with the inertial measurement unit (IMU). Since our initial plan to use the accelerometer for tracking the distance driven being too inaccurate, we had to come up with a unique approach to stay on budget. This is where our solution of using a photoresistor to count lights came into play. The second issue from the IMU was in relation to the magnetometer. We originally wanted to use the magnetometer as a compass to know what direction we were facing at all times. This functionality would also help account for drift caused by the motors and allow crisp turns at intersections of the tour. Unfortunately, the magnetometer was getting too much interference from the motors and battery to be usable. After attempting to move the IMU to different locations on the robot and lining the motors and battery with aluminum foil to shield the magnetic fields, we decided to abandon this sensor for the project.

B. Potential Changes to Method and Recommendations for Future Work

With the robot's current design, the algorithm used to maintain a straight and centered path is far from perfect. This flaw combined with the inaccuracy of the ultrasonic sensors means that the robot does not drive straight, but can manage to keep away from the walls. The first change that we recommend for future work is to look into more accurate sensors for this aspect. Some possibilities are encoders for the motors or a higher quality IMU.

Another recommendation for future work is to design the obstacle avoidance algorithm to be more robust and allow the robot to smoothly circumvent an obstacle. The path the robot currently goes around an obstacle is inelegant and it would look nice to have the robot detect an object sooner and take a more smooth and gradual path around it.

Team Member Contributions

A. Ammar Abdelwahed

Ammar, 3D design architect and electrical engineering major, contributed to many of the unique hardware design solutions required while also helping manage team operations and presentation/documentation writing. Although we were provided a robot kit, our project required a large array of additional components and hardware elements, often assembled ourselves and unique. As such, the mounting parts needed for the design had to be fabricated in order to ensure a clean and efficient final design. Ammar utilized his past experience with 3D CAD software to design multiple mounts, brackets, and casings for our components and custom circuit designs. This required communication with various department faculty to gain access to the appropriate printers and feedstock. This was especially important in the latter stages of the design, particularly the design of the photoresistor and speaker mount which would be essential to ensure correct operation. Additionally, Ammar handled much of the preparation and organization for documentation writing and presentations.

B. Sunay Bhat

Sunay, team leader and electrical engineering major, was largely responsible for hardware testing and integration along with A.J. Early on, the primary focus by Sunay was component testing and very basic software development. This included testing and early stage test code for the ultrasonic sensors, BMP180 pressure sensor, communication protocols, LIDAR sensor, and later on the photoresistor circuit. When the decision was made through the middle of the semester to attempt to move to a custom PCB, Sunay was the primary designer of this PCB. Using Eagle CAD software, he utilized open-source schematics and utilities to create a design that would emulate the operation of two Arduino Unos working in conjunction on a single board using a single power circuit. Later when the boards arrived, he assembled and tested the board set. Unfortunately, after working briefly, the completed board set failed due to undiagnosed issues, and due to time constraints the custom PCB design was abandoned. In the latter portion of the semester, Sunay worked to help assemble, debug, and continuously make design adjustments to the robot as needed with the rest of the team. Sunay was also responsible for communication, scheduling, and group assignment progress and submission as team leader. This included MBO write-ups and discussion with the course teaching assistants.

C. Clay Leach

Clay, computer science major, served as the software solutions engineer and hardware/machining engineer. Assisting Cody, Clay helped develop key components of the software algorithms such as the hallway centering code utilizing the ultrasonic sensors. He also helped develop the initial edge detection code that uses the infrared sensor to ensure the robot is capable of recognizing drop-offs and avoid falling. Clay also contributed to the physical assembly of the robot, including machining of a few components. The non-electrical hardware integration proved to be an extensive problem as the design evolved and required more components with increasingly complex circuitry. Clay addressed many of these issues when assembling components often using additional hardware, standoffs, bracket mounts, etc, that had to be acquired or custom designed. Working closely with Ammar on custom 3-D designs, Clay helped ensure a final hardware design would provide durability without sacrificing the testability and customizability needed to debug and test.

D. A.J. Toth

A.J., solutions architect and electrical engineering major, was responsible for hardware testing development along with Sunay, as well as software design required for location detection. In the early stages of the project, A.J. focused on building the algorithm for the inertial measurement unit that would allow the robot to know its location and improving the accuracy of the algorithm through different numerical methods. When the inertial measurement unit was deemed ineffective for our application, A.J. devised, developed, and tested the photoresistor circuitry that tracked ceiling lights of the Min Kao building as a second approach to location detection. He also assisted Cody in testing all required functions of the robot. Furthermore, A.J. attempted to take care of the responsibilities of team leader during times when Sunay was travelling or otherwise unavailable. Given the software-heavy nature of this project, A.J.'s largest contributions were in developing the methods and code required to implement various sensors, and assisting the lead software developer wherever possible.

E. Cody Treadway

Cody, lead software developer and computer science major, served as the primary software programmer, debugger, and system integrator for the project. Bringing extensive C++ development experience, Cody began early on in the semester writing the base block of the script that would serve as the final stage programs running the MKart. This would sometimes involve integrating pieces of code provided by teammates who had worked to test individual components, but he wrote the majority of code and programs that would be used to test the robot's various functionalities and final stage tour runs. Cody had to work closely with the primary hardware engineers, as the embedded systems nature of the project hugged the interface between hardware and software design. In this regard, Cody was able to constantly assist in hardware debugging and narrow the focus on the hardware design elements. In the latter stages of the semester, he would have to debug and run many iterations of a complex final program that would manage a full suite of sensors and various algorithmic elements. The I/O prioritization, interrupt handling, object avoidance techniques, and many other software objectives were accomplished by Cody's software contributions.

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Customer Agreement

Customer Signature: Mark E. Dean

Customer's Printed Name: MARK E. DEAN

Date: 4/24/2017

Team Member Signatures:

1. Ammar Abdelwahed: Ammar
2. Sunay Bhat:
3. Clay Leach:
4. A.J. Toth: A.J. Toth
5. Cody Treadway: Cody

Date: 4/24/17