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A Lab-Scale Autonomous Haul Truck for Underground Mine Operations: Design and Development

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A Lab-Scale Autonomous Haul Truck for Underground Mine Operations

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Abstract

The objective of this project is to facilitate the use of automation in an underground mining environment. In an active underground mine, there are several hazards a worker can face. The implementation of autonomous control of the mobile equipment used in these mining operations is one of the ways to cut down the number of injuries. It can also result in less time wasted for the workers as well as an overall safer mining environment. With autonomous vehicles in underground mines, it is less likely for accidents to occur involving mine employees. In order to implement autonomous control, several different types of sensors must be installed. The utilized sensors include multiple ultrasonic range detectors, and an image processing unit. These sensors provide complementary data to an Arduino microcontroller for collision avoidance and tunnel navigation, respectively. Experiments will be conducted to test the performance and reliability of the developed autonomous underground mine truck. The performance (timing) results from the experimental data will be analyzed and compared to those results from the manual mode of operation of the haul truck.

Introduction

In this project, extensive research was carried out on different sensors used in automation and localization of an object. Infrared was one choice, but due to some performance limitations, it was found to be not appropriate for an underground mine environment (i.e. a requirement for the line of sight of a stationary emitter) [1, 2]. A GPS was not selected in this project due to its limitation in an underground mining environment. Magnetic/inductive sensors could also pose serious issues in ferrous metal mines, where the sensors could get false positive readings. Instead, vision systems were evaluated showing promise for an underground mining application [3, 4, 5]. In [6], a Kinect™ sensor was utilized to allow the autonomous control of a follower vehicle. Various algorithms were used along with the infrared feedback of the Kinect™ sensor to allow the follower vehicle to "see" the leader vehicle and mimic its movements while keeping a certain distance away. In [7], a proportional (P) controller was used and showed that it worked well with the image processing unit used to control the lateral movement of an autonomous vehicle. Moreover, the control performance was improved by using a H∞ control technique, which is much more complicated than and not as reliable as the simpler P-controller. In [8], an image processing unit is used, which is fairly similar to the one used in this project. There were four different range detectors arranged around their autonomous vehicle, albeit infrared instead of ultrasonic. A Finite State Machine is used to select the particular program which should be running at a certain time. In [9], an autonomous vehicle was set up, comparable to a car, which could visually "see" and stay within its lanes on a model road. The experiment used a previous version of the same image processing unit, the CMUcam3, as well as some various laser sensors and gyroscopes. The camera was used to view and maintain its location within the lines of a standard road. The selected processor was not able to process the data quick enough to maintain a basic speed. The vehicle had to maintain a very slow speed; otherwise, it would behave erratically. In [10], the LIDAR and SLAM software were used to navigate through a multi-floor parking structure. It also showed what could be accomplished if experiments were scaled up with further funding, which would allow for expensive sensors. The SLAM software created a 2D recreation of the surroundings to be utilized by an algorithm for controlling lateral movement, as well as forward and reverse speed control.

In this research project, the operation of an underground mining vehicle is automated by utilizing four ultrasonic sensors for collision avoidance, and an image processing unit (Pixy CMUCam5) incorporated for area detection and track guidance. A lab-scale underground mine haul route was constructed for this project, based on which the data was collected for the manual cycle times through the haul route. The test course had a limited space to conduct the experiment with an exact replica, and so it was built within a 400 square feet (6.1×6.1 m^2) area. Within this area, the haul truck route was required to have a loading and dumping zone for the ore along with a passing bay and multiple sharp turns simulating a generic underground mine decline leading to the main orebody. The three main phases of operation for which automation is needed are the loading and dumping zones of the route, and where the truck has to turn around. The sensors used for navigation include a camera (Pixy CMUCam5) and multiple ultrasound sensors which are placed all around the dump truck.

Ultrasonic sensors and a vision system (Pixy CMUCam5) were chosen for this simulated underground mine haul route. These sensors were appropriate due to the lack of light and persistent accumulation of mine waste and mud in an underground mine. The camera differentiates between multiple colors to verify whether the vehicle is within the path of the route or either at the loading or dumping zones. The vision system will provide the microcontroller with the information that will determine which part of the control program to run. Moreover, the route is color coded, and so the colors will indicate which part of the program is needed to run. The ultrasonic range detectors are used as collision avoidance and will also contribute to the speed control mechanism.

In the first set of experiments, various bench tests were completed for the sensors and vision system (Pixy CMUCam5). These tests verified that the sensors would perform as desired. The preliminary tests that were performed were as follows. In the first set of tests, the truck was only to run through the course using a P-controller and ultrasonic sensors. Using the left and right ultrasonic sensors and not having the CMUCam5 attached, the truck completed half of the route before colliding with a wall. This exceeded expectations. Moreover, controlling of the lateral movement and truck speed was accomplished by using the Pixy CMUCam5. The test showed that we needed to refine our control method by utilizing the CMUCam5 along with the ultrasonic sensors. In the second set of tests, all sensors and the CMUCam5 will be attached to the truck. Once these sensors are in place, the control algorithms to allow the truck navigation will be created. When the truck reaches a loading or dumping zone, it will conduct a 3-point turn and then continue to go back through the route. Once the truck is able to complete the route, the performance (timing) results will be compiled and compared to manual control.

System Overview and Main Components

Vehicle:

For this project, the main component is a full metal 1/14th scale Armageddon Hydraulic Dump Truck [11]. The Armageddon is one of the most powerful and reliable radio controlled (RC) hydraulic hybrid lab-scale dump trucks available today. This European style dump truck was specifically engineered for transporting gravel, sand, snow, wood chips, and small rocks. Truck specifications are as follows:

- Length: 687mm / 27inch
- Width: 186mm / 7.3inch
- Height: 262mm / 10.3inch
- Weight: 8kg / 17lbs
- Recommended payload: 16kg / 35lbs
- Maximum lift power: 42kg / 92lbs

Microcontroller:

In order for the truck to function autonomously, the Arduino Mega 2560 [12] microcontroller is utilized. It is based on the Arduino Software IDE (a C/C++ based language which integrates other components in the project). The Mega offers a sufficient number of digital input/output pins as well as a considerable number of analog input/output pins. The Mega also has an increased flash memory storage capacity compared to smaller boards like the Arduino Uno or the Arduino Mini. The specifications are as follows:

- Uses C/C++ language functions
- 54 Digital Input/output pins
- 16 Analog pins
- 14 Pulse Width Modulation pins
- 128 KB of Flash Memory
- 5V Operating Voltage

Ultrasonic Sensor:

The four HC-SR04 Ultrasonic Modules [13] mounted to the four sides of the truck offer a collision detection system by sending out a short burst of ultrasonic sound. These sounds reflect off from the surrounding environment and then return back to the sensor. By measuring the time that it takes for the echo to return, the distance between the sensor and the nearest object are calculated. The specifications are as follows:

- Operating Voltage: 5V
- Operating Current: 15mA
- Effectual Angle: <15°
- Ranging Distance: 2cm - 400cm / 1” - 13ft

- Measuring Angle: 30°
- Dimensions: 45mm x 20mm x 15mm

Image Processing Unit:

In order for the truck to maneuver its way through the small scale mine shaft, the truck needs to recognize its surroundings. This can be accomplished by using an open-source hardware that is fully compatible with the Arduino Microcontroller. The Pixy CMUcam5 [14] created by Carnegie Mellon Robotics and Charmed Labs, is a small image processing unit that can be taught up to seven unique color signatures, and is able to compile the size and location of several hundred objects under a color signature while process a 640x400 image every 1/50th of a second. The specifications are as follows:

- Lens field-of-view: 75 degrees horizontal, 47 degrees vertical
- 50 frames per second
- 640x400 Resolution
- Can track up to 30mph
- Can learn up to 7 different color signatures
- Size: 2.1" x 2.0" x 1.4"

Desired Route

The small scale haul route for this project was handcrafted to meet the requirements of the trucks physical limitations while still simulating a generic underground mine haul route. Figure 1 shows the haul route that occupies an area of 400 square feet (37.21 m^2) and consists of a winding path with a graded gravel road supported by pressboard walls with an entrance and an exit area used to make a three-point-turn before either loading or dumping.

The desired haul route starts at the entrance and the truck has to navigate through the course. Once it reaches the end of the route, the truck will proceed to make a three-point-turn and wait to be loaded. After the loading procedure is completed, the truck will continue back through the tunnel and make another three-point-turn when it emerges to the "surface", dumps its contents (ore), and then the whole cycle is repeated.

Figure 1: Isometric view of the small scale mine route without ceiling.

Programming

There are two devices within the scope of the project that require extensive programming. This section will cover the programming and preliminary tests that were required for the HC-SR04 Ultrasonic Range Finder sensor and the Pixy CMUcam5.

HC-SR04 Ultrasonic Sensor - The Collision Avoidance System [13]

The first test on the ultrasonic sensor was conducted to ensure that each of the sensors worked correctly before testing the range, angle, and accuracy of sensors. Figure 2 is a constructed diagram that displays the ultrasonic sensor's field-of-view and angular viewing capability based on the distances that were used in the project.

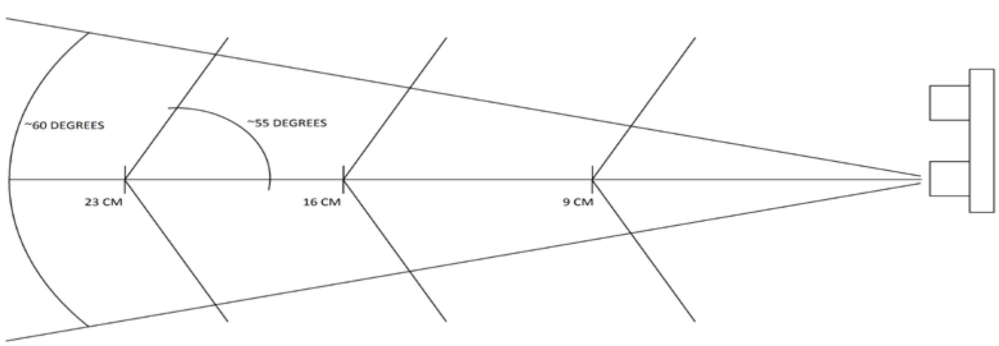

Figure 2: Conical field-of-view extruding from the transmitter part of the ultrasonic sensor.

After testing and identifying the limitations of the ultrasonic sensors, the programming phase was continued. The developed program required a function that took the reading from the sensor and converted it to a linear dimension. A test was performed in which the measured distance were taken from the ultrasonic sensors and were used to trigger a P-controller (on Arduino) for the steering wheel motion of the truck. This test is depicted in Figure 3.

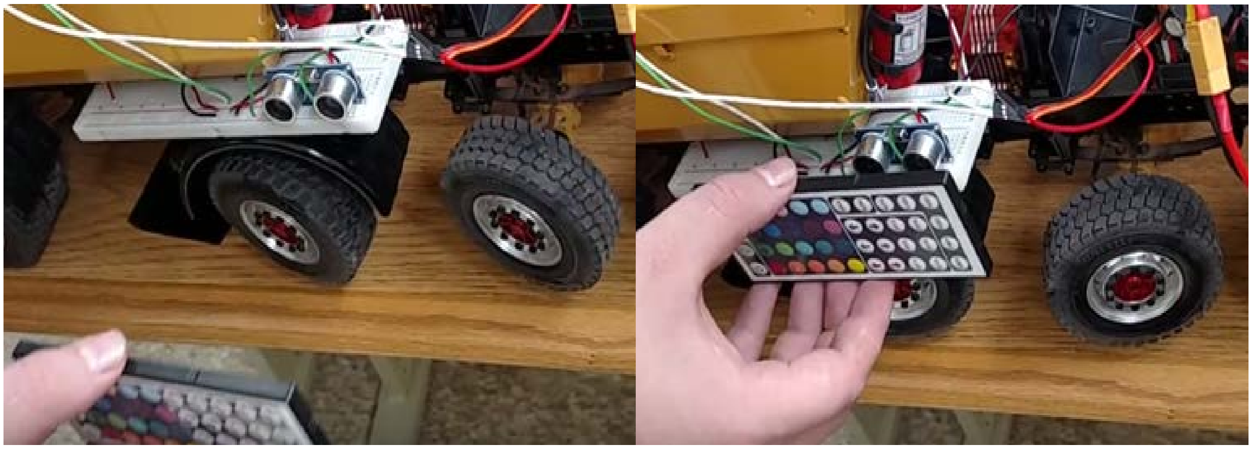

Figure 3: The truck steers away from an object that gets close to the ultrasonic sensor.

The preliminary tests were satisfactory, but the steering motion had some oscillations. Experiments with implementing proportional-integral-derivative (PID) controller for the steering wheel control were conducted in which only the proportional (P) part was used. After implementing the P-control, steering motion was much smoother than before, but it resulted in an overcompensating behavior in some corner turns. These corner turns can be eliminated when the integral (I) control will be implemented along with the P-control in the future.

Pixy CMUcam5 - The Image Processing Unit [14]

After assembling the Pixy CMUcam5 with the pan micro servo that came with the Pixy, the appropriate PixyMon software was downloaded and the first preliminary test was conducted in which the Pixy was programmed to follow an object as it moved around in Pixy's field-of-view. The Pixy camera recognized multiple color signatures and the pan micro servo was driven to keep the objects within the center of its field-of-view, as shown in Figure 4. Whenever a previously taught signature entered its field-of-view, the Pixy drove the pan micro servo to center the color in the camera's viewing field. When multiple (up to 1,000) color signatures were displayed to the Pixy, the pan micro servo kept positioning the Pixy appropriately to center the Pixy's field-of-view over all viewable signatures. This feature is beneficial for the main objective of this research project that the Pixy is required to follow a series of color signatures in the small scale mine haul route.

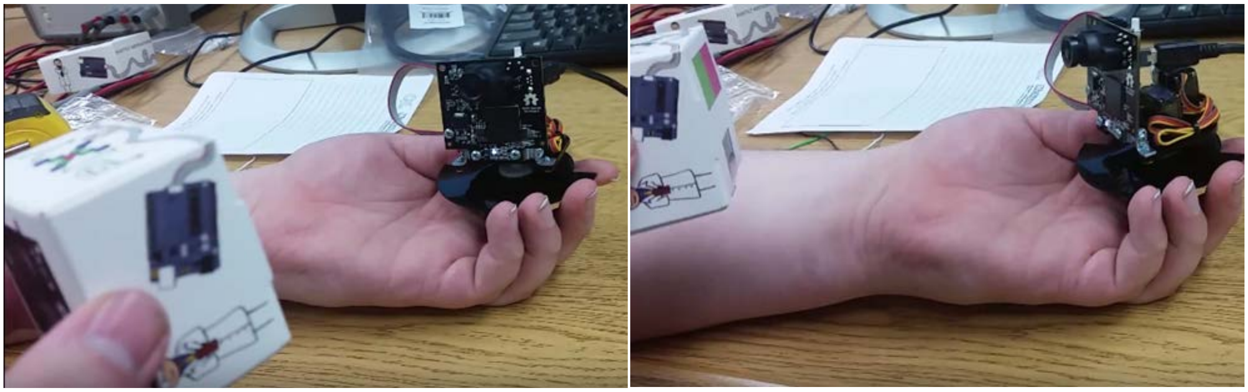

Figure 4: The Pixy camera sends out a signal to its servos in order to keep the box in the center of its field-of-view.

When the Pixy was mounted on top of the haul truck, the servo signal was sent to the truck's steering wheel servo instead of the pan micro servo that came with the Pixy. Figure 5 illustrates the next experiment in which the output pin of the Pixy's micro servo is connected to a standard servo that is comparable to the micro servo used to control the steering wheel servo in the truck. As a result, the standard servo would respond accordingly to the motion of the previous taught color signature in front of the camera, which simulates the respond of the steering wheel servo of the haul truck.

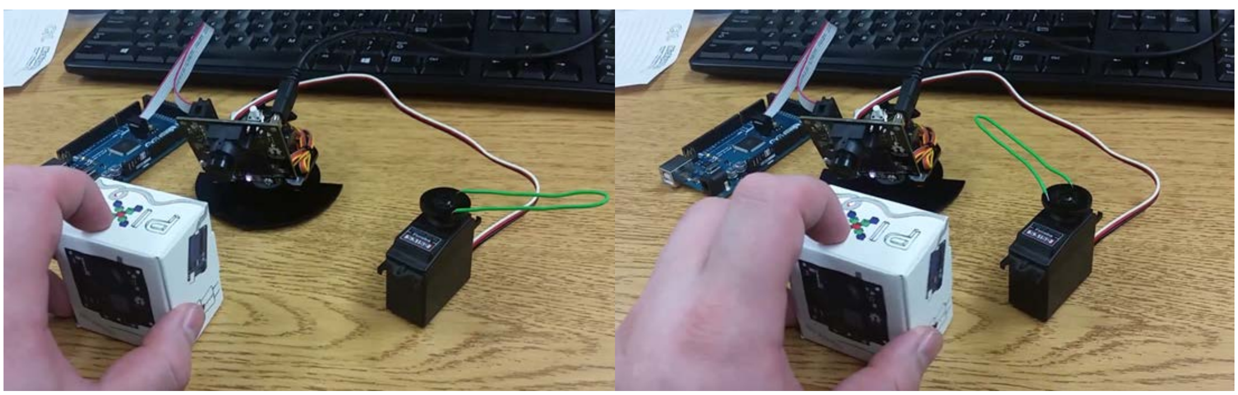

Figure 5: The green wire on the horn of the servo shows how the angle changes based on the position of the box in the Pixy's field-of-view.

After programming the Pixy to detect a color signature and keep it within the center of the camera's field-of-view, color swatches were used as a sign for the Pixy to follow. Figure 6 shows that the camera can easily detect the single color shown to it. Figure 7 indicates that the Pixy is able to detect and locate two objects of the same color in its field-of-view. The locations of these objects can be used by the microcontroller to control the truck along the mine track. Figure 8 shows that the Pixy can differentiate between multiple colors at the same time. This test shows that we will be able to utilize multiple colors to trigger the Arduino in order to select the program which is required to be ran at a certain point along the mine track.

Figure 6: Single color panel recognized on the Pixy CMUCam5 as “blue”.

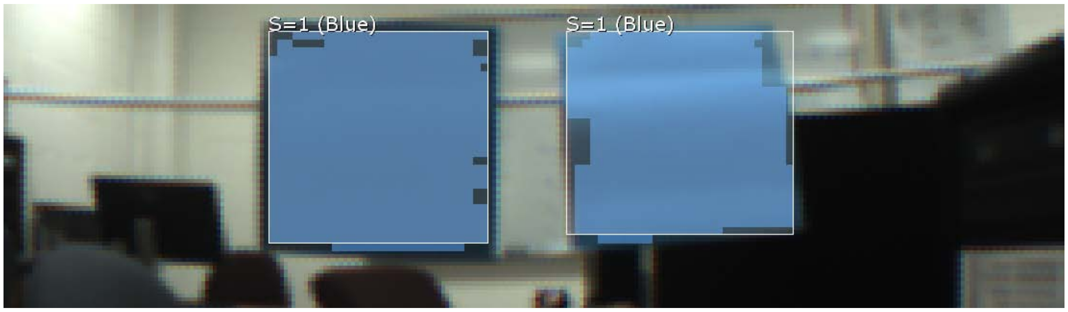

Figure 7: Pixy differentiating between two objects of the same color.

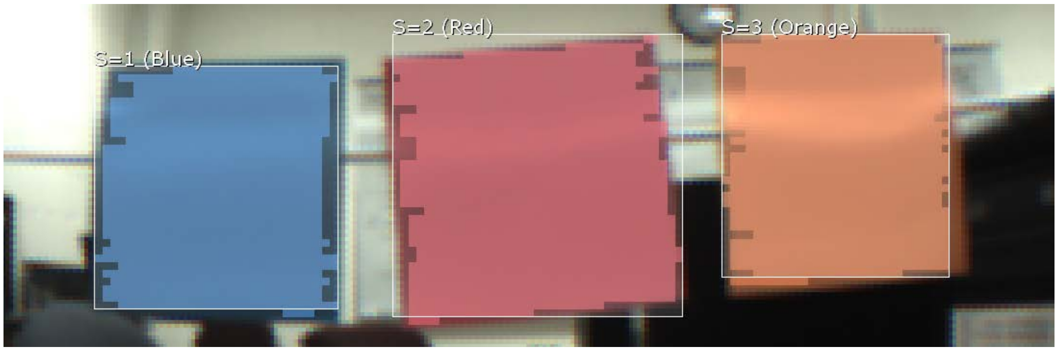

Figure 8: Pixy differentiating between multiple different colors, by detecting each of them as a separate instance of each color.

Wiring Diagram

In the original wiring diagram indicated in Figure 9, there are a few components that are not used in the scope of this project, which include the sound module and loud speaker, oil pump and its electronic speed control (ESC) unit, and locking differential servo. On the other hand, the components that are utilized in this project include the Li-Po battery, 320A brushed ESC, driving motor, and the steering servo. The 320A brushed ESC is used by the truck to control the speed of the main driving motor of the vehicle. The receiver is utilized when the “manual” mode of operation is turned on using the remote control (RC) unit, while it is not used in the “autonomous” mode of control which is the main focus of this research project. The original wiring diagram is designed for the “manual” mode of control in which the user-driven remote control communicates with the receiver on board the truck in order to send the control signals to manipulate the movements of the truck. In Figure 10, a switch, microcontroller, and various sensors were added to the wiring diagram in order to provide the “autonomous” mode of operation. In this new diagram, multiple units are utilizing the microcontroller's battery including the ultrasonic sensors, Pixy CMUcam5's image processing unit, and two additional micro servos used for controlling the pan and tilt of the camera.

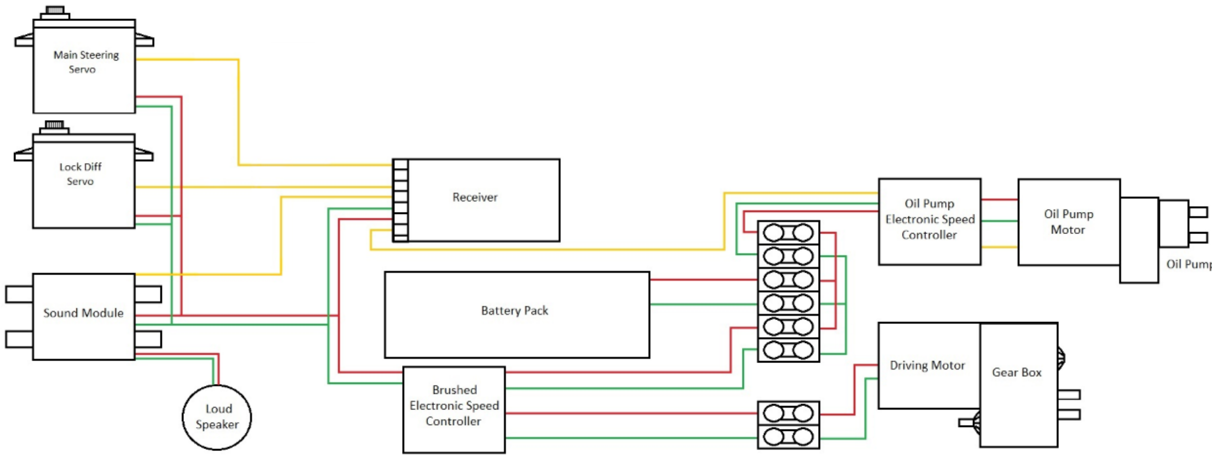

Figure 9: Original wiring diagram

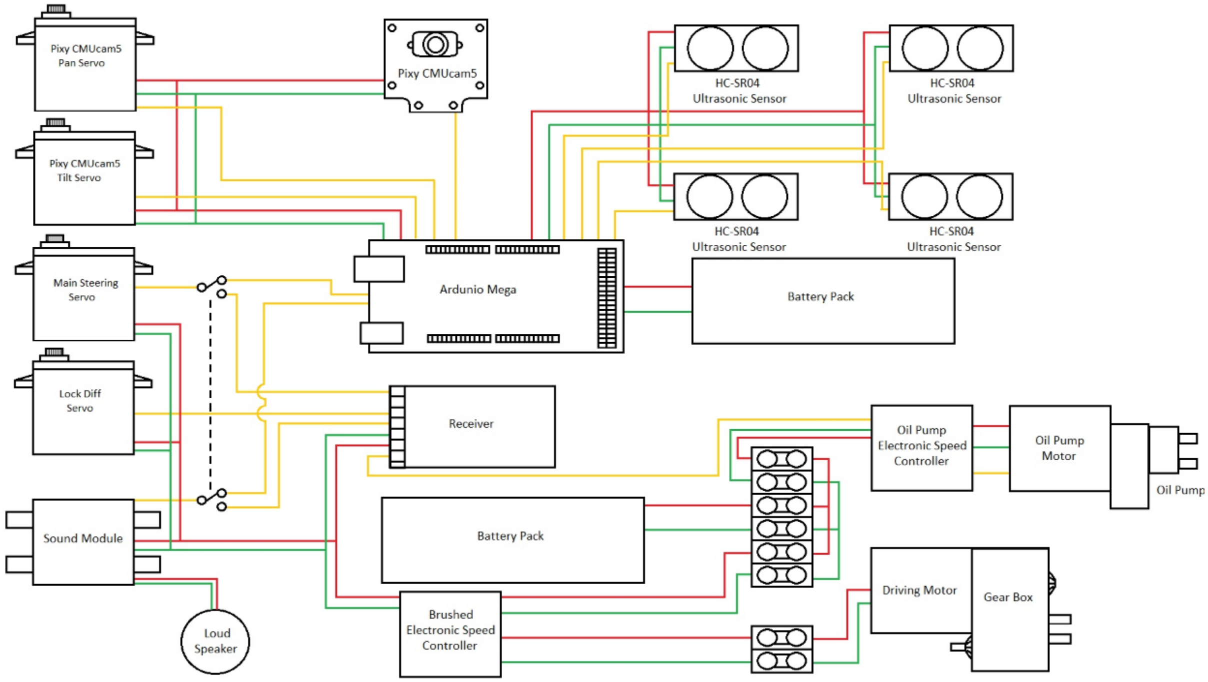

Figure 10: Modified wiring diagram which includes the Arduino microcontroller, battery pack, ultrasonic sensors, Pixy CMUcam5, Arduino battery pack, two servos for the Pixy, and control switch.

Conclusion and Future Work

The current results prove that the chosen sensors perform well in the lab-scale mining environment, and that the designed sensor and control system can be scaled up to a real mining environment. While outfitting the truck with the HC-SR04 ultrasonic sensors programmed with a collision detection algorithm, the proportional (P) controller yielded performance results that were quite satisfactory according to the specifications and requirements. The truck was able to move through half of the course by keeping an equal distance from the two walls of the lab-scale haul route. After the truck control was initially tested by using the ultrasonic sensors only, autonomous control was further tested in lab conditions by utilizing both the Pixy cam and ultrasonic sensors simultaneously. So far, we have been able to repeatedly drive through a third of the course autonomously. When the course is finished being outfitted with the color panels (swatches), it is expected that the truck will move along the whole route autonomously, and it will be able to repeatedly run the whole course back and forth without collision.

Based on the progress so far, the following plans are considered to be feasible in the future: troubleshooting the algorithm to achieve full autonomous control of the truck, fine tuning and final adjustments of the control program, obtaining test results (travel times) in autonomous mode, and comparing the results of autonomous mode with those of manual mode of operation.

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