Autonomous People Mover

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ABSTRACT

Most automobile forecasters predict that by the mid-2020's autonomous driving will transform the automobile market. What started with cruise control, then driver assist, and now highway autopilot, will soon develop into full autonomy. Autonomous vehicles will make our roadways safer, our environment cleaner, our roads less congested, and our lifestyles more efficient. This paper describes a multidisciplinary capstone project that is working towards turning a golf cart into a fully autonomous vehicle. Phases one and two of this project focused on making the golf cart remote controllable, while the current effort, and the bulk of this paper, is focused on making the vehicle drive autonomously within a closed course. Given a destination, the cart will plan a path based on the shortest distance and approved roadways. The vehicle will then precisely execute this path while detecting any obstacles in its way. The vehicle will do this by collecting data from various devices including GPS, LiDAR, odometry sensors, and several ultrasonic sensors. This paper discusses the innovative design, implementation, and integration of the various subsystems required for autonomous driving.

I. INTRODUCTION

The field of autonomous vehicles (AVs) has seen tremendous growth and investment in recent years [1]. While many advances have occurred, the technologies behind AVs are still nascent. Opportunities for continued research and development exist in several areas. The Autonomous People Mover (APM) was conceived as a vehicle for use in transporting people across the campus of Rochester Institute of Technology, a large academic institution in the northeastern United States. Once complete, the APM will be summoned via a text message, after which it would drive itself to the customer's location, pick them up, and determine a destination using voice recognition. The APM would then plan and traverse a path to the requested destination while maintaining the safety of passengers and bystanders. Ultimately, the purpose of the APM is twofold: to provide accessibility to campus goers, and to act as a platform for research and refinement of AV technologies.

II. BACKGROUND

The avenue selected for the initial design and build work for the APM was through a Multidisciplinary Senior Design (MSD) class. In this class, engineering students from a variety of majors work in groups to complete projects over the course of two semesters. The class structure dictates that the first semester be devoted to design, research, and planning, while the second semester is to be used for building and testing of projects. This year, the APM is being worked on by the third of three successive groups. In initial planning, the functionality requested from each group or phase was broken down as follows: Phase I- add remote control functionality to a golf cart; Phase II- add sensors required for autonomous driving and limited autonomous control; and Phase III (current phase)- add full autonomous control. Because of unforeseen delays and necessary redesign work, the current team of students is working on goals midway between Phases II and III.

In the current phase, the APM is being designed to localize itself, accept a user destination, plan and traverse a path from its current location to the destination, and avoid static obstacles along the path. This is accomplished with the aid of hardware for actuating the steering, throttle, and brakes; a computer and microcontrollers to process sensor data and control the APM; ultrasonic rangefinders, a high-accuracy GPS module, and a LiDAR system for environmental perception and localization. Efforts have been made to ensure that the APM will always operate safely. A fail-safe emergency stop feature ensures that power will be cut from the drive motor and the brakes will be applied when a system fault is detected, when a passenger hits the stop button, or when the stop button is triggered remotely.

III. DESIGN

Driving Modes

Manual mode will be the default mode of operation for the APM. This mode is controlled by the factory supplied brake, throttle and steering wheel. The braking actuator is not used in this mode but he wicked steering system is because it adds power steering to make the steering wheel easier to turn. Although it is not needed because a person is in control of the APM, the E-stop will still be functional in manual mode. No additional sensor information is used to control the APM in this mode.

Remote mode is selected through a RC transmitter. This mode will be controlled using a braking actuator, a wicked steering rack, and PWM signals from the microcontroller to the APM's throttle controller. Two wireless PWM signals are used for this mode of operation, one for brake and throttle and the other for steering. The APM can be put into an emergency stop state by activating the Emergency stop (E-stop) button on the APM or on the remote. When an E-stop is triggered, the

APM returns to manual mode. No additional sensor information is used to control the APM in the remote mode.

Autonomous mode is selected through the user interface. This mode will be controlled using the braking actuator, the wicked steering rack, and throttle PWM signals that are sent from the microcontroller to the APM's controller. The APM's position and heading are determined using an onboard GPS. The APM's position is used for feedback in determining how well the path planning algorithm is being followed. An onboard CPU maintains a control system for all of the subsystems and uses the serial bus to communicate with the microcontroller. The steering system is implemented using a Proportional Integration Derivative (PID) feedback loop using an encoder mounted on the steering rack. Similar feedback systems control the braking and speed control using a brake encoder and speed tachometer respectively. The APM is able to detect objects in front using a LiDAR for light reflecting objects and seven ultrasonic sensors for sound reflecting objects. The APM reacts to objects by either stopping or driving around the objects. In autonomous mode the E-stop stops the APM and returns it to manual mode.

Emergency Stop

The Emergency Stop (E-stop) system provides to the passengers a fail-safe method of stopping the cart. The design of the system utilizes a push button to trigger three actions. The first action signifies to the system that an emergency stop has been activated. The second action causes a break in the "Main Switch Line" (Key) which disconnects power to the APM motor. The third action engages the brake actuator to stop the cart and prevent any further movement. These actions ensure that the APM and its passengers are in a safe state in the case of software error or hardware failure.

The design of the E-stop as shown in Figure 1 utilizes a hardware-only approach to engage each action. This approach minimizes reaction time and isolates the system such that failure in other components of the cart won't affect the reliability of the E-Stop.

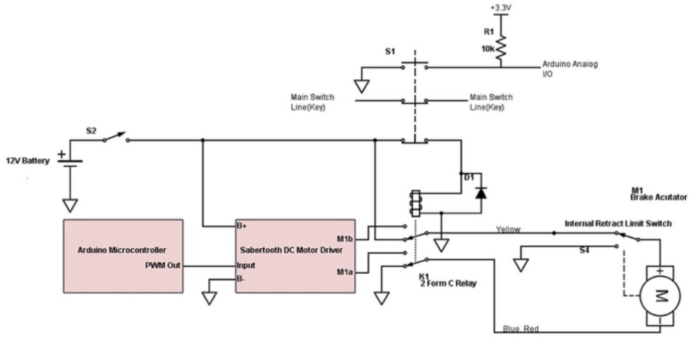


Figure 1: Emergency Stop Circuit.

Hardware

The control system of the APM is comprised of a desktop computer, two microcontrollers and a main printed circuit board (PCB). These three components work together to interpret feedback from APM and the surrounding environment to produce logical action that allows for safe autonomous driving. The desktop computer is used to interface with the LiDAR and microcontrollers and performs all computationally heavy tasks. These tasks include image processing, path planning, and sensor interpretations. The microcontrollers are used to engage steering, throttle, and brake as well as read from numerous sensors including ultrasonics and encoders. The main PCB encompasses additional control and level shifting circuitry and provides connection between the stock vehicle controller, the microcontrollers, and the onboard sensors.

Ultrasonic Sensors

In order to ensure the safety of riders, pedestrians and the vehicle itself, detecting objects is an important feature of all autonomous vehicles. One of the methods selected for object detection was ultrasonic rangefinders. The Maxbotix MB7363 HRXL-MaxSonar WRLS and MB7001 LV- MaxSonar- WR1 sensors are used in this application. The MB7001 has the ability to detect objects within 6.4 meters and the MB7363 has the ability to detect objects within 10 meters of the device. There are 7 ultrasonic sensors placed on the front of the APM, three being the MB7001 and four being the MB7363. The ultrasonics are connected to the Sensing Microcontroller. Pin 3 of each ultrasonic module is connected to a different analog to digital input on the microcontroller. Pin 4 of each ultrasonic is connected to a PWM pin on the microcontroller. The PWM is used to ensure the ultrasonics ranged simultaneously. The analog voltage read in by the microcontrollers is converted to its corresponding value in inches. The data is passed to the computer where it is used in combination with knowledge of the position and orientation of the sensor to determine where an object is in the three-dimensional space around the cart.

LiDAR Sensor

Light detection and ranging or LiDAR is a technology that has seen significant improvements in cost and utility in recent years. The APM is equipped with a VLP-16 Velodyne Lidar Puck which uses infrared laser pulses to measure the distance to objects and reports them as a three-dimensional point cloud. This sensor has a range of 100 meters with a 360 degree horizontal field of view and ±15 degree vertical field of view. The VLP-16 was placed in the front of the APM and was connected to the onboard computer via Ethernet. The Lidar data can be used to distinguish people from stop signs and is mounted to see fast moving objects within 180 degrees in front of the APM.

The VLP-16 was used for broader range object detection while the ultrasonics were used to cover narrower range object detection in order to provide detection redundancy within the APM's immediate path. The goal with the placement of these sensors was to ensure there were no detection gaps or blind spots in front of the APM. The LiDAR and ultrasonic data is overlaid on the same three dimensional graph. If an object comes within a certain range of the APM's planned path, the APM will slow down, brake, or reroute around the object in the path.

One of the most important abilities the APM is its ability to localize itself. For this task, both the APM's location on the planet and its trajectory are required to know where the vehicle is and where it is going. A Global Positioning System (GPS) became a clear solution to these problems

GPS

There are a lot of options in the market today for GPS modules, depending on requirements for budget and accuracy. Most inexpensive commercially available units are accurate to two or three meters. With our own testing of such units, we found that while in open terrain with good atmospheric conditions, these GPS units may have worked well enough for our purposes. However, more accuracy is required when operating close to tall buildings and in small spaces.

Getting more accuracy requires one of two technologies, either a Differential GPS which utilizes a base-station GPS unit and location GPS unit, or a Real-Time Kinematic (RTK) GPS, which needs a connection to the internet and is designed to compute corrected positions off of data from a network in real time. Both of these options typically get accuracies down to the centimeter scale, but their cost can be significant. However, in the past year or so the price for the RTK option has significantly declined. In the fall of 2016, SkyTrak released a S1315F8-RAW RTK board. A custom Printed Circuit Board (PCB) was designed to interface with the unit. The design is show as Figure 2, layout as Figure 3, and a picture of the fabricated and mounted board is shown as Figure 4.

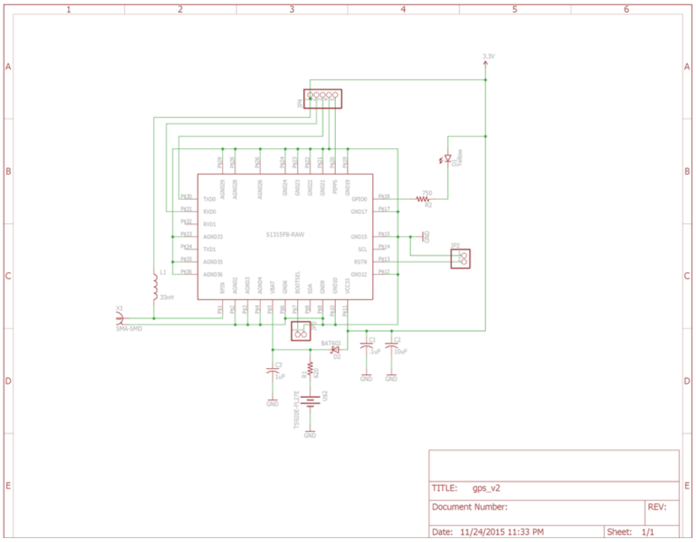


Figure 2: GPS PCB Design.

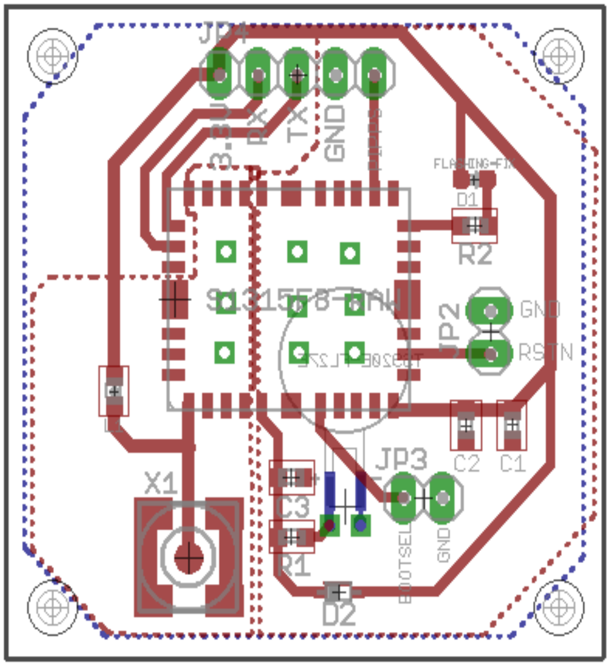


Figure 3: GPS PCB Layout.

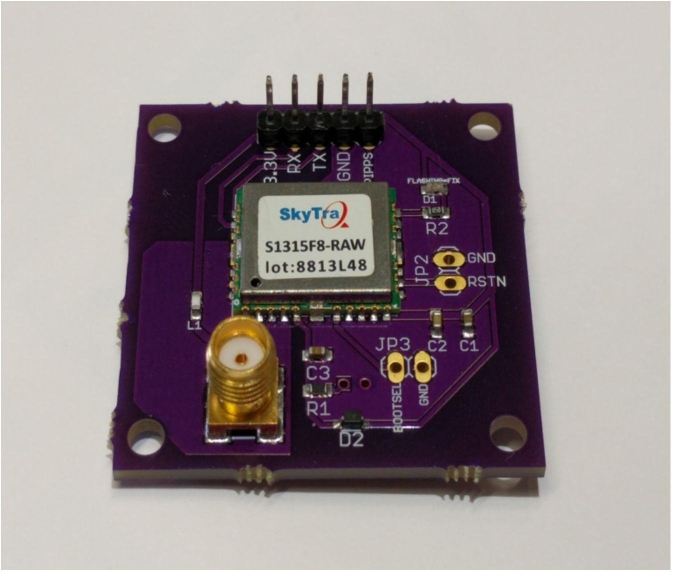


Figure 4: Custom Printed GPS Board.

This PCB allows for the S1315F8-RAW to connect to the computer via a serial connection. Using the open-source software called RTK Lib, NMEA sentences with the GPS information are reported.

Software

The APM's software can be split into two major categories, the software that runs on the computer and the software that runs on the microcontrollers. Both are source controlled in the same repository using GIT.

Computer

The computer CPU is an AMD Opteron(TM) Processor 6272, running Ubuntu 14.04 LTS. It has a keyboard and mouse that can be connected via USB, however most of the time making changes to the computer is done over an SSH connection. For the purpose of development all of the team utilizes virtual machines that mirror the APM's computer for development and staging before final testing on the actual APM.

The major software component on the computer is the Robot Operating System (ROS). ROS is an open source set of software libraries which provide a framework for developing robots. It contains tools for interfacing different types of IO devices such as LiDAR, libraries for doing localization and map making, and lots of other useful tasks for autonomous robot control. The APM computer software leverages the ROS environment to break down functionality into ROS nodes, each of which publishes and subscribes to topics to communicate between each other. A larger overview of the software systems is shown in Figure 5.

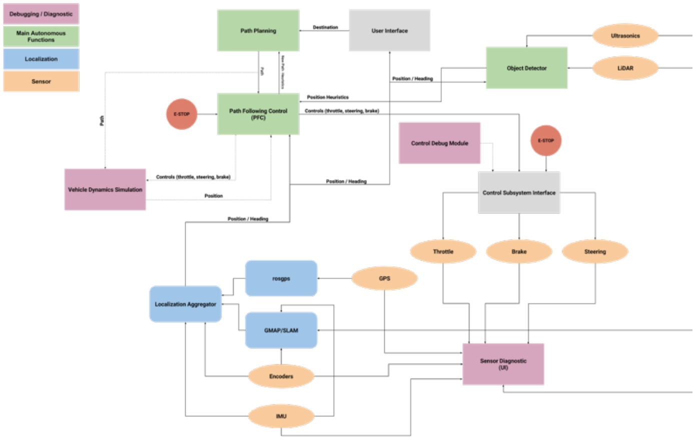


Figure 5: Software Block-diagram overview.

The major software components include the Path Following Control (PFC), Path Planner, Obstacle Detector, Localization Aggregator, Diagnostics Module, Debug Module, and the Vehicle Dynamics Simulation.

Path Following Control

The highest-level software component is the Path Following Control (PFC). The PFC combines the localization and odometry data from the Localization Aggregator, the path solution from the Path Planner, and the list of preferable, nominal, and invalid positions from the Obstacle Detector to output the control that will go to the subsystems. It also has an emergency-stop state which can be entered at any time where it outputs the emergency stop output (0% throttle and 100% brake) as a backup measure, if for some reason the physical emergency stop system was to fail.

The PFC must first determine if it is ready to calculate updates to the controls or if it needs to make some kind of a path correction. To do this it must first request its current environmental state in the form of preferable, nominal, and invalid positions from the Obstacle Detector. Then the environmental data is compared to the location of the cart with it's heading from the odometry data being used to decide whether or not there is an imminent danger or if the there needs to be a path correction.

If there is an imminent danger, then the rest of the process is short-circuited and the cart's software enters a software-triggered emergency stop state which will reset when the danger has passed. If a path correction is required due to the current planned path not being valid in the future, the Path Planner is given the new heuristics based on the current environmental conditions and very rapidly responds with a new path to follow.

After the path is determined to be valid for the foreseeable future, a new set of commands is generated for the controls by calculating the difference between the current location and next location, as well as the current heading and target heading.

These processes continue while the cart is in run mode, and once the destination has been reached, the cart re-enters a ready mode awaiting a new destination. An important note is that the destination has a required heading and speed of zero, this ensures that the cart will calculate a smooth deceleration as it reaches the destination.

Path Planning

The main job of the path planner is to use a saved map of valid points and their connections to generate lowest-cost paths to and from points on a map. The APM has a list of valid waypoints that have been drawn out in advance by a human describing the location of paths and other valid places to drive. This is done using Google MyMaps paths, and extracting the points from the exported path. Assuming that all waypoints are of a similar relative distance to each other, the minimum distance that ensures every point will have at least one neighbor is used as the area in which nodes will become neighbors. This then takes the points that were drawn on the original path and generates a graph that can be used for path planning. In the future, having the APM automatically modify and add points to the graph is desired.

The lowest-cost path is found using an efficient implementation of A*, which is written in C and uses heuristics as well as the distance (cost) of the path through the nodes. This is queried often by the PFC as the APM's environment changes and it disables certain nodes in the graph due to obstacles. The Path Planning software returns a path solution as an ordered series of waypoints the APM will plan on moving between.

Object Detection

The Object Detector has one task, and that is to take the data from the environment around the APM and use that data to score the points in the area around the cart. It does this using a variety of sensors including seven ultrasonic sensors and a forward-facing LiDAR sensor.

The location of the ultrasonics is known, and by using the distances returned from them a good picture of the objects in front of the car can be determined. Using the known location and heading of the APM, the distances can be overlaid to decide if and when they are going to interact with the path. Given that the ultrasonics are queried many times for every small distance the APM moves, a constantly updating picture of what is ahead of the vehicle typically allows the PFC to plan far in advance to avoid static objects. The Object Detector has no knowledge of what region each of the objects is in, but reports objects in the environment as well as lower than nominal scored areas to the PFC.

Moving objects are more difficult to predict and react to, the most difficult being ones that move across the front of the cart because they give the least amount of time to react. As the object moves in front of the cart and is detected by the sensors, the object detection will inform the PFC where it is and the PFC decides what the corrective action will be. The object will fall into one of the regions (imminent danger, correction, observation) and the PFC will decide what to do.

Diagnostics and Debugging

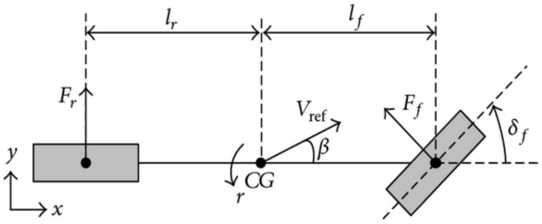
Diagnostics and Debugging tools are essential to the development and continued use of the APM. To facilitate quick debugging and ensure the safety of the cart, there are a variety of tools for ensuring the correct operation of the vehicle systems. The diagnostics are available at any time and can be displayed by pressing a button on the user interface. It shows the status of all of the available sensors on the APM. Debugging tools can be launched by the microcontrollers or computer, and these allow for testing the different outputs, limits, subsystem tuning parameters, and circuits on the APM. While the debugging tools are not expected to be used as part of normal operation, they allow for quick discovery of issues by testing individual as well as integration behavior.

User Interface

The user interface for the APM is a full-screen GUI application that runs on an on-board touch-screen monitor. Its primary purpose is to allow for the user to switch between the modes of the APM (Manual, Remote Control, Autonomous), as well as interact with those modes. It also has a button for diagnostics which shows the status of every available sensor. In autonomous mode, it currently shows a list of predefined destinations for user selection.

Vehicle Dynamics Simulation

In order to test control logic in a resource inexpensive environment, a vehicle dynamics model of the APM was constructed and simulated using MATLAB. The model used was a standard three degree of freedom "bicycle" model as described in Figure 6.



$$\dot{x}_1 = \frac{\left(aP_f\delta + bF_{\xi f} - bF_{\xi r}\right)}{I}$$

$$\dot{x}_2 = \frac{\left(P_f\delta + F_{\xi f} + F_{\xi r}\right)}{m} - x_3x_1$$

$$\dot{x}_3 = \frac{\left(P_f + P_r - F_{\xi f}\delta\right)}{m} - x_2x_1$$

$$\dot{x}_4 = -x_2 \sin x_6 + x_3 \cos x_6$$

$$\dot{x}_5 = x_2 \cos x_6 + x_3 \cos x_6$$

$$\dot{x}_6 = x_1$$

$x_1 = \dot{\theta}$ yaw rate
$x_2 = V_\xi$ lateral velocity
$x_3 = V_\eta$ longitudinal velocity
$x_4 = x$ longitudinal position with respect to fixed reference
$x_5 = y$ lateral position with respece to fixed reference
$x_6 = \theta$ yaw angle

Figure 6: Single tract three degree-of-freedom model and associated state-space equations [2] used for MATLAB simulation.

For the APM simulation, the first order differential equations from the state-space model are solved with the ode45 command in MATLAB. Control inputs of steering angle and rear tire force (a proxy for accelerator and brake application) are determined prior to the solution of the differential equations. For this reason, the equations are solved iteratively with control inputs occurring between iterations. Through simulation, the correlation between forward velocity, steering angle, and turning radius are recorded and used to define turning radius as a function of forward velocity and turning radius (quantities that are measurable on the APM). This allows the simulation to be able to project the anticipated location of the APM at a given time into 2D space. This information in combination with the minimum stopping distance of the APM is used to define a safety bubble for which an intrusion by an obstacle will trigger an emergency stop. A secondary safety bubble is constructed from the resulting paths of all possible steering angles at a given time. If there is an intrusion into this secondary safety bubble, then the steering angles that will result in entrance into the primary safety bubble will be eliminated from the range of steering angles from which the algorithm can select.

Subsystems

All of the control subsystems (steering, throttle, and brake) are controlled by one microcontroller. This microcontroller runs a program that is connected over serial to the ROS environment running on the computer. It takes commands for the throttle, steering, and brake as well as outputs some diagnostic values over various ROS ‘topics’ that it publishes and subscribes to. It subscribes to a topic which tells it what mode the APM is in, so it can decide what commands (remote, autonomous, manual) to control with.

Steering

The steering system for the APM is powered by an electric power steering rack. The steering rack normally would take a differential signal from an integrated torque sensor and use that to decide how much torque to assist with. By utilizing a single digital-to-analog converter on the microcontroller as well as some level shifting and scaling circuitry, a differential signal that mimics a torque sensor is generated. The power steering system is controlled by a +/- 5V differential signal centered at 2.5V. This circuit, as shown in Figure 7, converts a 0.55V – 2.75V DAC output to a +/- 5V differential signal centered at 2.5V. The 2.5V center is critical because the power steering controller will throw an error code if it does not receive this. A potentiometer was added to the steering rack in order to provide a feedback mechanism for sensing the position of the steering rack by the microcontroller. Changes in the position of the steering system are measured as a change in voltage across the potentiometer via an analog-to-digital converter on the microcontroller.

The steering control subsystem runs on a microcontroller. It takes commands for values from 0-100%, where 0% is full left turn, 50% is center, and 100% is full right. Given a desired set position, a proportional controller is used to effectively drive and minimize error in the steering subsystem.

Throttle

The speed of the golf cart is controlled by a JU2-H1890-10 Advanced D.C. motor located on the back of the vehicle. This is a 3.5HP motor with a class H rating. In the stock golf-cart configuration a throttle pedal outputs a 0-3.3V signal into the golf-cart motor controller. The APM throttle subsystem takes the throttle pedal as an ADC input, and outputs a value via a DAC. The DAC outputs from 0.55-2.75V however, so an additional circuit, figure 8, was added to amplify and shift the output of the DAC to a 0-3.3V range.

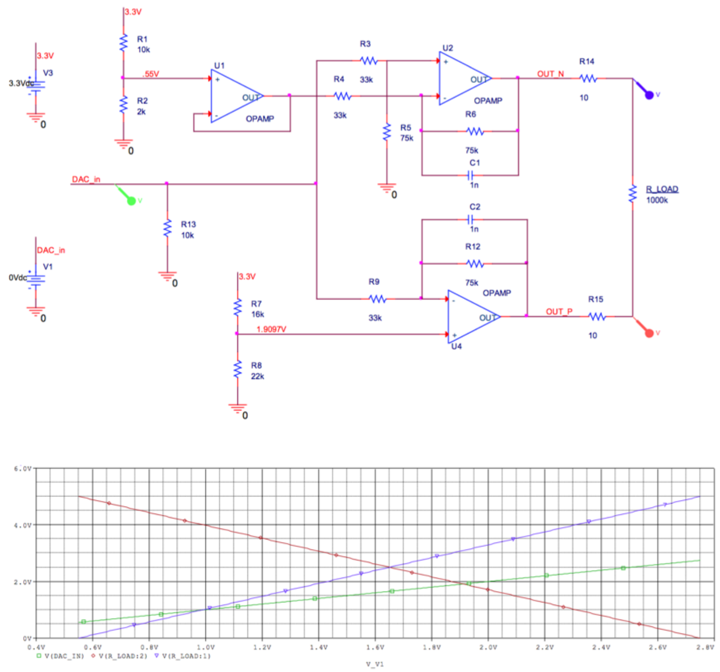


Figure 7: Steering Control.

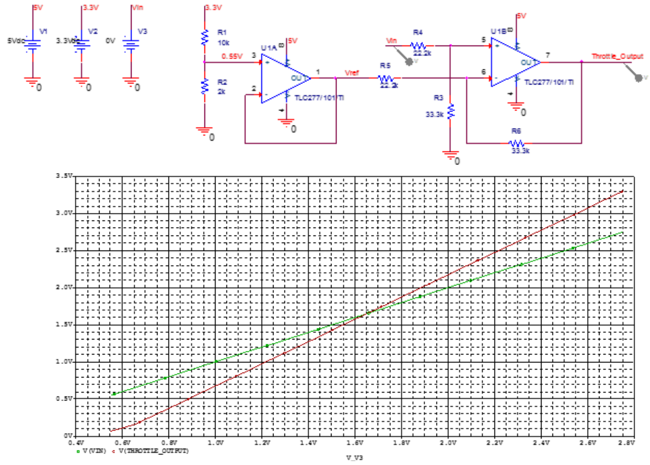


Figure 8: Throttle Amplification and Shifting Circuit.

Brake

The brake is actuated by the Thomson E150 Actuator, which is driven by a Sabertooth 2x12 R/C connected to the microcontroller. The Sabertooth 2x12 R/C converts a standard servo-control signal (1-2ms pulse at 50Hz) to 12V voltages across three wires. These three wires are configured so that the actuator extends with a 1ms pulse, stays where it is with a 1.5ms pulse, and retracts with a 2ms pulse. The brake actuator has a built-in potentiometer, which is read to give the position of the actuator. Due to this potentiometer being so close to the actuator, there was a lot of noise on the signal. To combat this, an RC low-pass filter was added to reduce noise. The brake subsystem control code running on the microcontroller uses a PID system to extend or retract the actuator to reach the desired position, which is given as an amount of brake applied, from 0%-100% where 0% is no brake, and 100% is full brake. The Sabertooth does not vary the voltage applied across the actuator to allow the PID control to work properly and dampen oscillation. There is another layer of control which incorporates a certain number of delay cycles to slow the motion of the actuator when the PID system requires it.

Weatherproofing

In order to ensure reliability of the APM, care was taken to protect vulnerable equipment from environmental hazards. With the addition of electronic equipment throughout the APM, isolation of components and electrical connections from water intrusion took highest priority. The majority of the added electronic hardware was housed in an electronics enclosure mounted on the rear of the APM. The enclosure was made water resistant by sealing gaps around ventilation grates and cabling pass-throughs. The brake actuator and electric steering system, which are located outside the enclosure, possess their own weather protection. The LiDAR and ultrasonic sensors selected claim waterproof operation. A final layer of protection was added in the form of water-resistant electrical connectors that were used for all connections outside of the main enclosure.

Occupant Monitoring System

The ability to monitor the occupants in the APM allows for safe and efficient operation of the cart. This system provides feedback to the control system regarding whether there are passengers in the cart and allows the vehicle to halt when certain unexpected scenarios are encountered. The scenarios can include passengers exiting while vehicle is in motion. If this was to occur, the APM can briefly pause operation to allow re-entry or proceed to next task if re-entry doesn't occur.

The occupant monitoring system on the APM utilizes dual ultrasonics aimed at the seat of the vehicle. The ultrasonics are able to cover the entire span of the seats from the far left to the far right. The control system will periodically poll the ultrasonics to read the distance of objects from the sensors. The sensors are calibrated by obtaining readings when the seats are empty. A threshold value is included to ensure bags or boxes are not interpreted as a passenger. Statistical values including average and standard deviations are used in the interpretation algorithm.

Energy Monitoring

Adding an energy monitoring system to the APM ensures safe and reliable autonomy for the vehicle. This allows the APM to determine if the batteries need to be recharged or replaced. The device used to monitor this is the TF01N which is a coulometer that measures battery voltage, current and power. The voltage and current measured have +/- 1% accuracy. This device has an LCD screen that displays the battery voltage, battery current, remaining battery capacity and remaining time of charging/discharging. The Sensing microcontroller receives the data from the TF01N and processes it to determine the status of the battery and if the APM has enough battery to make another trip.

Pedestrian Notification System:

To improve the safety of the APM while traveling, an audible beeper and strobe flash system was added to notify pedestrians of its presence. The system was designed to notify pedestrians in front of the vehicle, so the sounder and light were directed forwards. The LiDAR was used to detect objects in front of the vehicle. The detection signals were sent from the computer to the microcontroller over a serial connection. If objects were within a specific distance from the APM then the sounder and/or light would be turned on. A secondary benefit to the system is that pedestrians would steer away from the APM, so there would have to be fewer adjustments in travel.

IV. CONCLUSION

While much progress has been made on the APM, there is much work yet to be done before the initial vision is met. Before the APM can safely be allowed to operate in an open environment, rigorous testing is being conducted to ensure the robustness of all subsystems where safety is a concern. Currently, the APM lacks rear vision. This could potentially lead to scenarios in which the APM does not take appropriate action for certain hazards, e.g. a cyclist overtaking the APM from the rear. Another hurdle the APM will face is the requirement that a safety driver be present at all times. This is a requirement of most AVs currently in development [1].

Significant improvements can and should be made to the sensing abilities of the APM. In the case of LiDAR, the currently installed VLP-16 unit offers enough high-fidelity data that 3D SLAM would provide opportunity for extraction of a wealth of information relevant to autonomous navigation, thus a major task for the future will be to better leverage the existing LiDAR capabilities of the APM. Other sensing technologies that are commonly used in AVs are radar and stereo vision cameras. Both of these would help to refine the APM's perception of its environment in 3D. Stereo cameras would also help in identification of and differentiation between object and terrain types (e.g. telling grass from pavement), as well as granting the ability to read road signs and markings.

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