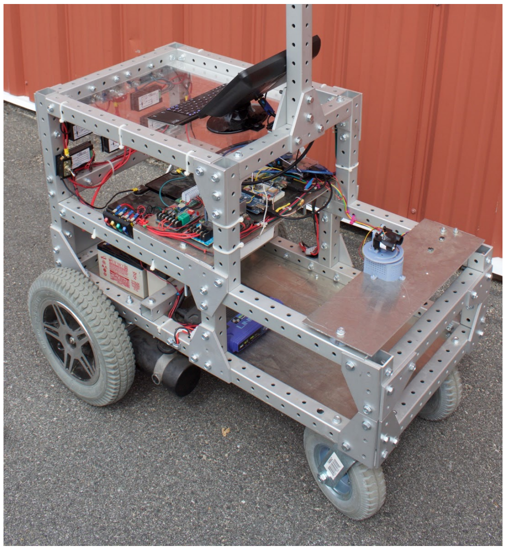
IGVC2017-SPARKY

ROGER WILLIAMS UNIVERSITY FIRST GENERATION INTELLIGENT GROUND VEHICLE REPORT



Roger Williams University
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As the faculty advisor for the 2016-2017 Roger Williams Intelligent Ground Vehicle Competition team, I hereby certify that the engineering and design that has gone into the creation of the 2016-2017 IGVC has been significant and equivalent to six (6) credits in an engineering senior design course.

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ABSTRACT

The Intelligent Ground Vehicle Competition (IGVC) is an annual international multidisciplinary robotics competition held at Oakland University in Rochester, Michigan. This year, in the competition's 25th year, the Roger Williams University IGVC Team, with robot Sparky, will compete for the first time. Last year, the Roger Williams University team was unable to complete the requirements to qualify for the competition on time. This year, Sparky will compete in the design competition as well as in the Basic Autonomous Navigation Course. This report will outline the mechanical and electrical design and software strategies employed to implement the 2016-17 robot.

INTRODUCTION

The Intelligent Ground Vehicle Competition is an annual international multidisciplinary robotics competition held in Rochester, Michigan. Over the past 25 years, the competition has become known for its difficult challenges and courses. This year, the Roger Williams University (RWU) IGVC Team is competing in the Basic Autonomous Navigation Course.

The RWU Intelligent Ground Vehicle team is composed of students performing their senior design capstone project. This is the second year that this project has been implemented as a capstone project, and the first year that RWU will compete in the Intelligent Ground Vehicle Competition in June of 2017. As a part of the senior design capstone project, the group spent two semesters in design and implementation of the IGV, subject to certain constraints. The most significant constraint for this project was the limited budget. The total budget for the project was \$4825, with \$3625 contributed by the RWU School of Engineering and \$1200 provided by the RWU Provost's Fund for Student Research to defray travel expenses.

The 2015-16 senior design IGVC team was unable to design, implement, and test an autonomous robot, which would be able to complete the basic qualifications, and therefore did not travel to the IGV competition. This robot suffered from inadequacies in mechanical design, electrical sensor integration, processing power, and algorithm design.

Mechanical shortcomings of the 2015-16 IGV design included frame weakness and poor fabrication, as well as no way to secure electronics, processors, or the 20 pound payload. The 2015-16 design was implemented using a welded steel frame, which was heavy and could not be easily modified. As a result, a new frame was designed and fabricated by this year's team. In terms of electrical and software shortcomings, the 2015-16 system lacked the ability to navigate autonomously while avoiding obstacles, which is the primary goal of the IGV Competition. The system could be manually driven and could perform rudimentary waypoint navigation, but lacked an integrated compass, LIDAR, or camera. This year, the electrical team designed and implemented an autonomous mode that uses waypoint navigation, obstacle avoidance, and line detection. This report outlines the design, prototyping, and fabrication of a new frame and the implementation of an autonomous system.

TEAM STRUCTURE & DESIGN PROCESS

Team Organization

The 2016-17 Roger Williams IGVC team consists of students specializing in mechanical, electrical, and computer engineering. The team is organized into two primary groups: a mechanical group and an electrical/software group. The mechanical group was tasked with designing and assembling a new frame, the overall vehicle packaging, the design and implementation of the mechanical stepper-LIDAR, and the installation of other various sensors. The electrical/software group was tasked with electrical wiring, power management, and the selection and integration of processors, sensors, and batteries. In addition to hardware considerations, one of the primary responsibilities of the electrical/software group was the design and execution of the system software for autonomous navigation. Although the group was split, all major design decisions were discussed and agreed upon as an entire team. The team captain's tasks included scheduling weekly meetings, organization of group tasks, and maintaining forward progress in semester long goals. Weekly meetings were held with the advisor to discuss progress on the IGV and upcoming milestones, which needed to be accomplished.

Design Assumptions & Process

The design objectives included minimizing manufacturing expense, designing a modular frame that would be easy to modify, and meeting the minimal requirements for qualification. The basic frame design specifications as outlined in the IGV requirements are that each vehicle must be a minimum of 3 ft. long, 2 ft. wide, less than 6 ft. high, and be capable of carrying a 20 pound payload measuring 18" x 8" x 8". In addition, the platform is required to include a mechanical and wireless emergency stop, as well as a safety light that blinks when the vehicle is in autonomous mode and remains solid while in manual mode.

Since this is Roger Williams University's first time attending this competition, some assumptions about the competition format, execution of deliverables, how the course is laid out, and ground conditions had to be made. One of these assumptions is that the platform would need to hold a significant amount of weight while being made out of a lightweight frame in order to not to hinder the torque or speed provided by the motors. Another assumption is that the incline of the ground would vary throughout the competition, requiring all components to be secure, which was verified on the IGV through testing on an incline. The final design assumption is that the robot must be fabricated to last multiple years, as the future IGV team will primarily focus on electronic design and the waypoint algorithm.

The design process involved three primary design problems: the frame, sensor choices and placement, and software design. The first problem that was addressed was the frame design. The frame was designed, tested via simulation, and fabricated during the fall 2016 semester. Using the criteria and design assumptions outlined in the IGVC manual as a guideline, materials and frame types were researched to make informed design decisions. Aluminum was chosen for its high yield strength and lightweight characteristics. In addition, hollow 8020 aluminum was chosen for its modular properties, which allowed the team to decide on sensor placement at a later date. After deciding on the material, different frames were designed in SolidWorks and graded based on design criteria. Once the frame was chosen, a prototype was constructed using cardboard tubing. From this prototype, it was apparent that the robot was too wide, and as a result the frame width was reduced by 6 inches. With this alteration in mind, the frame was fabricated to produce the final design.

While the frame was being designed and built, the electrical/software team began coding and testing sensors on the 2015-16 IGV platform. In addition, the electrical/software team began software design and chose appropriate sensors for autonomous navigation. These choices are explained in more depth in the electrical design section. Related to this, another important design consideration was sensor placement for appropriate operation. The sensor placement also informed the frame design, and the platform was tiered to provide an appropriate location for delicate electronics. An enclosure was designed and produced for the camera, and an assembly integrating the LIDAR with a stepper motor was also designed and fabricated.

Effective Innovations of Vehicle Design

A number of innovations were implemented in the design and fabrication of the IGV. The first of these innovations was the choice of the 8020 aluminum. The aluminum was chosen because its interior can be used for wire routing, it is lightweight, it has a high yield strength, and it is modular. Because the tubing is hollow and lightweight, less of the motor torque is required to transport the weight of the frame, allowing for additional weight due to carrying electronics and the competition payload. The large cross sectional area of the aluminum increases the moment of inertia and the high yield strength gives further structural support, making the design less likely to fail through bending or buckling. Another benefit of the 8020 aluminum was the modular design. The aluminum has holes spaced every 1.5 inches, which was utilized for placing sensors and routing wiring. The modular tubing will also be useful for future IGV teams to allow for easy modifications to the vehicle without a requirement to weld.

Another cost effective innovation was the application of a one-dimensional LIDAR in combination with a stepper motor to afford 2D functionality. The cost to obtain a 2D or 3D LIDAR that functions in sunlight is several thousand dollars, which was beyond the scope of the IGV budget. The original design concept was found via research and was modified to meet the purposes of the IGV competition [1]. This original design implemented a gear train to translate the rotation of the stepper motor to that of the LIDAR. After printing and testing with the modified design, significant improvements were made to reduce gear noise, add ventilation, and incorporate a hard-stop to prevent drifting within the stepper motor. The resulting design directly attaches the LIDAR to the stepper motor, which eliminates the gears. In addition, this design includes ventilation holes and a hard stop using a slot and pin design. This implementation cycles 180 degrees at a frequency of 0.67 Hz for object detection and avoidance. This is adequate for a first attempt, but may need to be sped up in future iterations.

To provide necessary processing power, a Raspberry Pi is used as the central processor and Arduino microcontrollers perform signal processing and conditioning for sensor subsystems and send this data to the Raspberry Pi via serial communications. The camera is connected directly to the Raspberry Pi to afford the use of OpenCV for image processing.

MECHANICAL DESIGN

Overview

An autonomous vehicle is immobile without an appropriate frame design. The frame must be strong and lightweight while meeting the IGVC required dimensions, maintaining mechanical integrity when subjected to motor torque and payload requirements, and maintaining predictable dynamic behavior. The previous frame design was poorly fabricated from steel and was difficult to modify. This frame was studied so this year's team could make informed design decisions concerning the mechanical aspects. The new frame was selected from viable alternatives by applying a decision matrix and SolidWorks linear stress analysis simulations.

Another important design aspect was the application of a stepper motor in combination with a one-dimensional LIDAR. This application utilized a 3D printed assembly to implement a low-cost solution that obtained the functionality of a 2D LIDAR without the financial deficit. The initial design concept was taken from existing research on an open-source website [1], but through testing the design was found to be inadequate in ventilation, noise, and drift. In order to improve upon these weaknesses, a new assembly was created. The refined design can be seen in the LIDAR-Stepper Design section below.

Frame Design

Using the physical size constraints as outlined by the IGV requirements listed above and lessons learned from observing the previous frame design, a number of feasible designs were identified and modeled in SolidWorks. These designs were considered and a decision matrix was used to select the best potential design.

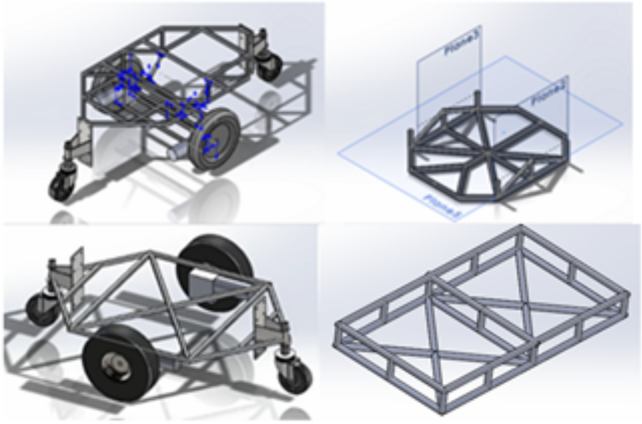

Figure 1: Original SolidWorks for possible frame design

The criteria for selection were ease of fabrication, use of material (weight), and the apparent stress concentration of the design. The first iteration of feasible alternatives is shown in Figure 1.

	Ease of Fabrication	Weight	Stress Distribution	Score
Top Left	17	18	18	53
Top Right	13	16	14	43
Bottom Left	17	18	17	52
Bottom Right	20	17	18	55

Table 1: Decision matrix depicting frame scores for initial designs

After evaluating these designs, it was evident that the top right design would be inadequate. However, it was not immediately apparent which of the other three designs would be most effective. To determine this, a static linear stress analysis was performed in SolidWorks for each of these three designs. The loading forces were placed on members where the wheels were to be attached and where the payload would be placed. The results of the FEA simulation in SolidWorks are shown in Figure 2. The blue and red coloring within the FEA analysis represents areas of lowest and highest possible stresses, respectively. Other colors, such as green and orange, represent the gradient of stresses in between. The main purpose of the FEA analysis was to identify which design optimized the use of the material and created the least amount of stress concentration. Stress concentrations within the FEA analysis can be identified by significant sections of blue or red coloring.

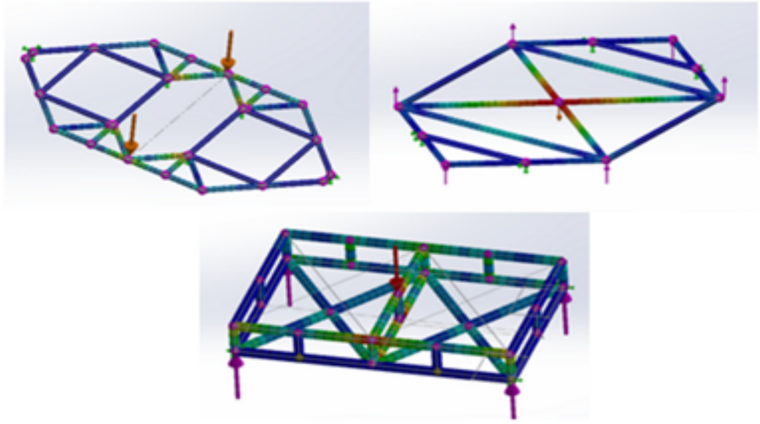

Figure 2: Static Analysis of SolidWorks frame designs
(Top: two frames chosen for analysis, Bottom: Additional frame)

From the SolidWorks analysis, it can be seen that the top designs did not optimize material usage and created stress concentrations. Both of the top designs in Figure 2 did not distribute the loading to the front or rear of the vehicle, which can be seen by the significant blue shading. However, the third frame distributed the load to various parts on the vehicle as seen by the various areas of green shading. Although the bottom frame did display some of the lowest stress concentrations, these low stress concentrations were located in sections where the heavier components were to be mounted.

Based on this analysis, the third design was chosen because it provided an appropriate mechanical structure for the moving frame. From this process, new design considerations were weighted with more importance. These new considerations included simplicity, manufacturability, modularity, functionality in terms of housing electronics and weight. One of the main problems with the previous frame was that it could not be modified or added to without welding, cutting, or drilling – changes that could not easily be undone if a design decision was reversed. A second layer was then added to the frame model to ensure that smaller electrical components and microcontrollers could be easily accessed. The cross beams that were originally there for support were taken away in favor of using flanged tubing. The chosen material was 8020 aluminum tubing, which is pre-drilled at 1.5 inch spacing. Brackets and mounting hardware are standard for the material and improve manufacturability, making the design easier to modify.

Once the new design was modeled in SolidWorks, a cardboard tube frame was constructed to give a spatial representation of the new frame. This prototype allowed for an improved idea of how the motors, wheels, and casters would be placed. In addition, with the created cardboard frame, it was observed that angled structural members would not be easy to fabricate and attach, therefore these cross braces were removed from the design. The primary frame structure was designed and fabricated during the fall 2016 semester but small modifications were made during spring 2017 to secure electronics and payloads. As these design improvements were made, the SolidWorks model was updated accordingly, as seen in Figure 3.

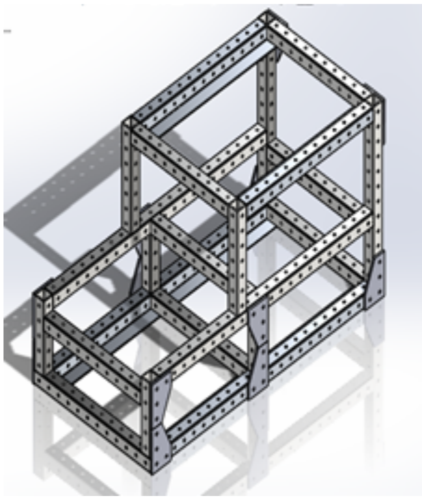

Figure 3: Final SolidWorks design with 8020 square and flanged tubing

Suspension Design

Initially, the intent was to develop, model, and test a suspension system for the platform to reduce mechanical vibration in the structure. However, as alternatives were considered, it became clear that fabrication of such a system would be expensive in terms of cost and fabrication time. The 2015-16 iteration of the IGV platform used hard rubber caster wheels that were small in diameter, did not roll well in grass, and were inadequate for carrying a heavy payload. The replacement casters installed by this year's team are larger diameter pneumatic tires, which can alter the ride by releasing or adding air pressure.

LIDAR-Stepper Design

Once the fabrication of the frame was complete, one of the main tasks of the mechanical team was modifying a one-dimensional LIDAR to provide 2 dimensions of data for obstacle avoidance. As previously described, the primary design constraint was that the platform should be low-cost, and traditional 2D and 3D LIDAR systems did not meet this constraint. Through research, the innovation of combining a one-dimensional LIDAR with a stepper motor to achieve the functionality of a 2D LIDAR was utilized [1]. The identified design was modified to meet the requirements of the IGV platform, and was fabricated by 3D printing. The initial design had several weaknesses: the gears created noise interfering with signals, the stepper motor began to drift over longer periods of use, and the stepper motor would overheat within the casing. Due to these deficiencies, the assembly was redesigned and fabricated to achieve the design goal while mitigating the problems with the initial design.

The upgraded design, as seen in Figure 4, improves upon the deficiencies in the initial design. The new design utilizes ventilation holes for heat dissipation, a pin and slot hard stop to prevent the stepper motor from drifting over the specified 180 degrees, and a direct attachment from the LIDAR to the stepper motor eliminating the need for a gear train.

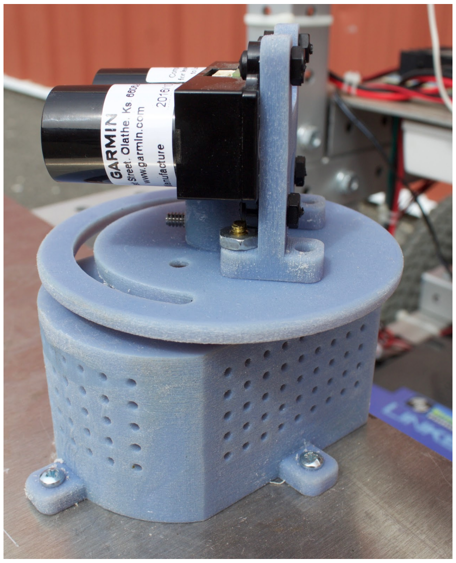

Figure 4: Fabricated final LIDAR assembly

Fabrication

The frame was fabricated by the end of the fall 2016 semester to allow the electrical/software group time to move electronics from the old platform and to allow significant time for software development and testing. Prior to this, the software development and testing of the electrical components occurred on the 2015-16 frame. The modular nature of the aluminum tubing expedited the fabrication process and improved the manufacturing accuracy. The convenience and strength of the standard mechanical fasteners also rendered welding unnecessary. In addition to reducing the time to fabricate, the use of mechanical fasteners in place of welding reduces the permanence of the frame structure, which was one of the shortcomings of the 2015-16 iteration. This system also allows for valuable flexibility and ease of modification, and has the unexpected benefit of improving wire routing in the IGV. Another consideration in the frame fabrication was weatherproofing, which was achieved through the use of acrylic and vinyl affixed by hook and loop fastener.

In the spring 2017 semester, several non-structural frame modifications were made to the design to house electronics, batteries, and the payload. Specific modifications include the addition of a battery support bar, a camera stand, and a base-plate for the LIDAR assembly, which is hinged to easily access the 18” x 18” x 8” payload. The finalized platform is shown in Figure 5. The LIDAR-stepper assembly was also fabricated in the spring 2017 semester by 3D printing using the Stratasys Objet 30. The final LIDAR is shown in Figure 4.

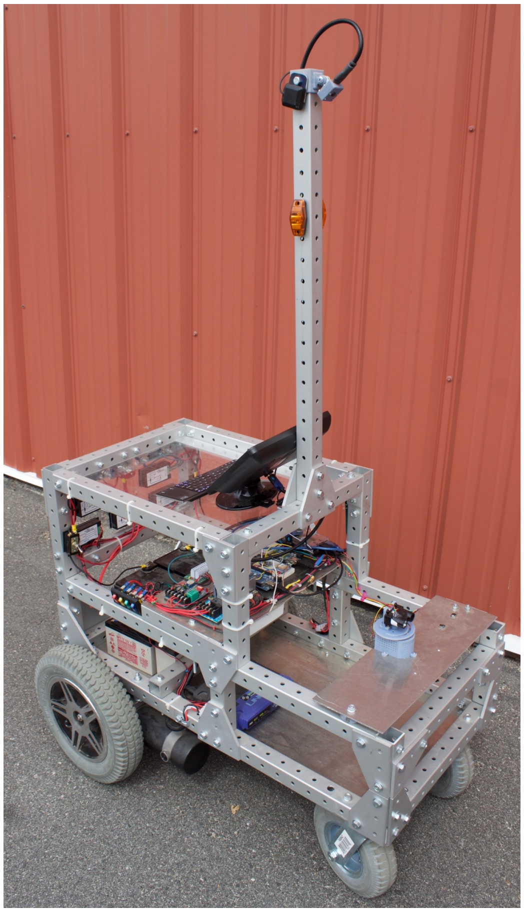

Figure 5: Final fabricated design for the 2016-2017 IGVC

Safety Considerations

The safety requirements for the IGV are a remote emergency stop and a mechanical emergency stop. The integrated remote kill switch has a range of 100 ft. and has multiple remotes in case other members see hidden problems. The platform is also equipped with a push-button, mechanical emergency stop on the back to allow power to be cut when near the robot. In addition, lights were implemented per the IGVC requirements. If the vehicle is in autonomous mode, the lights will flash, and if the vehicle is in manual mode, the light will remain on and solid.

ELECTRICAL DESIGN

Overview

While a frame is an important facet of a robot platform, electronics and processors make up the heart of the IGV. The electrical design for the IGV consists of four different subsystems of integrated sensors. The sensor subsystems include GPS for localization, orientation sensor for trajectory information, LIDAR for obstacle detection, and camera for line detection. The data from each of these sensors are fed into microcontrollers which condition and process the data and make basic decisions. The conditioned data is then transferred to a Raspberry Pi, which is used for navigation decisions, image processing, and delivering commands to the motor controller. The entire system is powered by five 12V batteries.

Sensor Choices

1. GPS: The Adafruit Ultimate GPS Breakout with a 10Hz refresh rate is used for IGV localization. This device has an accuracy of about 3m, and can obtain information from up to 22 satellites to track its location. In order to boost accuracy, an external antenna is connected to the GPS Breakout to increase sensitivity by 165 dB/m. This data is conditioned in an Arduino Mega, which delivers processed data to the Raspberry Pi. This GPS was selected because it is compatible with the Raspberry Pi and was fairly accurate for the team's limited budget.
2. Orientation sensor: The Adafruit BNO055 Orientation Sensor is a nine-degree of freedom inertial measurement unit (IMU), which determines the absolute orientation. Orientation data is processed in a separate Arduino Uno, and the resulting information is transferred to the Raspberry Pi. This sensor was chosen because, with the nine degrees of freedom, was more accurate and provided more data, including roll, tilt, and pitch in addition to the compass heading.
3. LIDAR: The LIDAR could have potentially been an extremely expensive component for the IGV platform. Since budget was a significant design constraint, the chosen LIDAR is a Garmin LIDAR-Lite V3 one-dimensional LIDAR, which was converted into a 2D lidar using a lidar assembly previously explained in the mechanical section. The LIDAR data conditioning and stepper control is handled in an Arduino Uno. This LIDAR uses a 905-nanometer laser beam to calculate the distance of any object within 40 meters of proximity. The accuracy of this LIDAR is 2.5cm and the entire assembly monitors five regions to avoid obstacles, which is covered more in depth in the software section.
4. Camera: A Raspberry Pi V2.1 8MP camera is used for image processing. The camera operates at 1080p 30 fps resolution and captures the front view of the robot to identify the location of white lines, potholes, and flags. Once an image is captured, it is processed using openCV software to detect various obstacles. This camera was chosen because it is compatible with the Raspberry Pi and provided the clearest image out of all cameras tested.

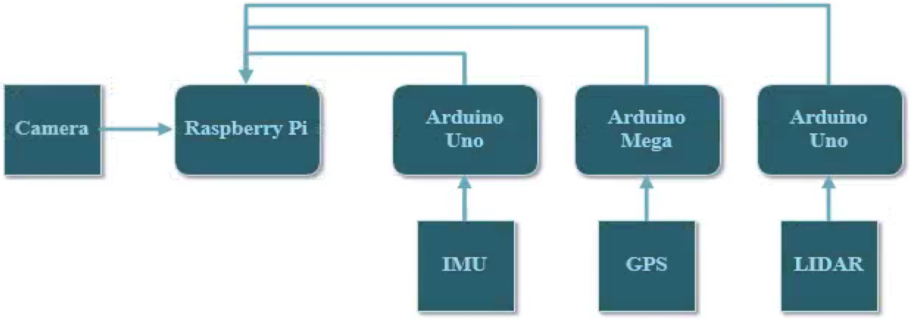

Figure 6: Diagram of the electrical system

Power System

The power system in this intelligent ground vehicle is primarily run off 12V batteries. Using a combination of two 12V 35aH lead-acid batteries, the servos are powered in series. This power combination allows 6-10 hours of continuous movement depending on operating speed. In addition, there are three 12V 7aH batteries that individually power the stepper motor, remote kill switch, and router/on-board monitor. All of the batteries have battery monitors installed to prevent power failure. The servo batteries recharge period is approximately 10 hours and the 7aH batteries recharge period is 5 hours.

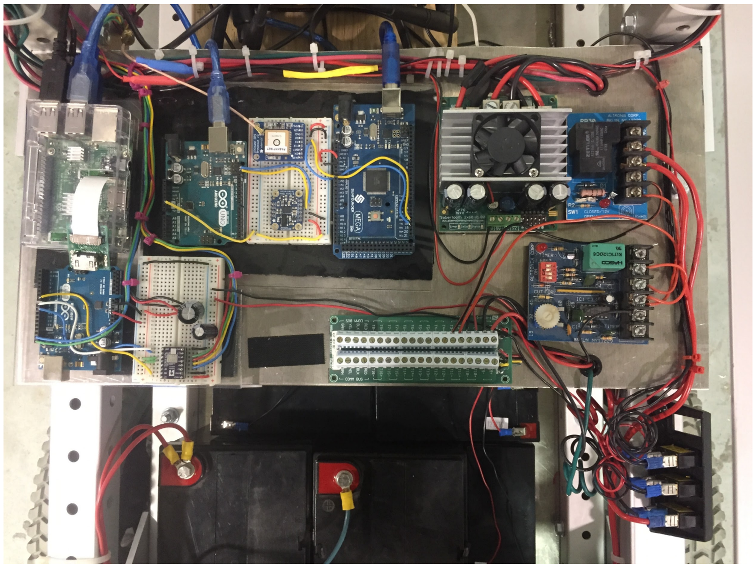

Figure 7: The IGV platform's electrical system setup

SOFTWARE STRATEGY

Overview

The software approach to the competition was to focus on avoiding the obstacles in the path and staying within the lines while traveling towards the waypoint destination. Sensor subsystems were programmed in C++ on the Arduino microcontrollers. The main program was implemented in Python on the Raspberry Pi.

Operating System

The platform's main software system is run in the Raspberry Pi 3, using Python 2.7 with the Geany compiler. The Raspberry Pi reads in and parses the data from the compass, the GPS, and the LIDAR, all powered from separate Arduinos.

Navigation

The navigation system is based off of a series of state transitions in a main program, which call external definitions for updating the sensors, calculating bearing, and calculating distance to the waypoint. The IGV reads in data from the compass to determine where it is facing, and then uses the GPS to determine the distance it is away from the waypoint. If the platform is not within 10 degrees of the desired bearing, it will continue to correct itself until it is within the acceptable range, and then drive forward until the next check. Additionally, if the platform is less than 10 meters away from the destination, it will continue to loop through the turn to and drive forward process until it is within the acceptable distance range.

Obstacle Detection & Avoidance

The obstacle detection and avoidance is handled primarily with the LIDAR. The LIDAR is constantly sweeping, however, the data is only read in and utilized as the platform is traveling forward. The LIDAR sweep is broken into five regions - to the left, left center, center, right center, and right of the IGV - and uses a series of 1s and 0s to determine whether or not there is an obstacle within 6ft. A “0” indicates that there is nothing in the region, and a “1” indicates that there is an obstacle present. The various combinations of 1s and 0s were analyzed, and each were assigned to a motor command that corresponds to where the platform should be traveling to, either left, right, forward, or backward. Once the obstacle has been avoided, the robot will continue to move towards the waypoint until another obstacle has been found.

Line Detection

The line detection is handled using the video feed on the camera. The camera remains on while the platform is running in autonomous mode, and by default will travel how it is dictated to through the navigation unless it sees a white line marker. If this occurs, the camera will pick up a series of line segments, and will draw a line from the highest and lowest points, which the IGV is instructed to avoid left or right dependent on the angle the drawn line segment makes with the horizontal axis. Otherwise, if the IGV picks up no lines, it will continue on as it was.

Integration

The integration of the navigation, the obstacle detection, and the line detection systems follows a predetermined logic system. The IGV will first search for lines with the camera and sweep for obstacles with the LIDAR simultaneously. If a line is detected, the platform will respond by turning parallel to it and continuing on. If an obstacle is detected, the robot will respond accordingly by either turning left, right, or backing up depending on which region the obstacle is sensed in. Otherwise, it will check the GPS coordinates and the distance away and continue straight with the ultimate goal of reaching the waypoint.

TESTING & VEHICLE PERFORMANCE

Performance Testing

For the competition, the IGV must travel to a given waypoint while avoiding obstacles and staying within the lines. To verify that the platform could accomplish this, a variety of performance tests were conducted.

For waypoint navigation, multiple waypoints were tested to determine if the IGV could accurately and efficiently navigate to these destinations. Once the platform was able to navigate to within 10 meters of the destination while maintaining an average speed between 1 and 5 mph, obstacles were added into the tests. The team obtained traffic barrels to test with, and positioned them in the navigation path to demonstrate obstacle avoidance. Once the integration of obstacle avoidance was verified, image processing was included in the algorithm to check for lines. Lines were placed first in a straight path, and then in a curved pattern to determine if the platform could avoid the lines on its way to the waypoint. When this was achieved, obstacles were added to verify that all subsystems had been integrated correctly. These experiments were used to inform improvements and bug fixes to the algorithm until all requirements for qualification and the basic course were satisfied.

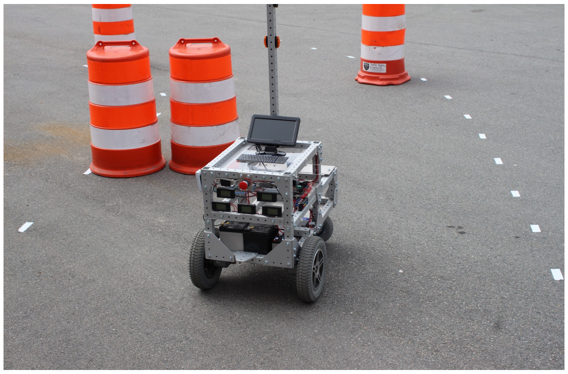

Figure 8: Picture of the platform navigating through a sample course avoiding obstacles and within the course width of 10 feet between the lines

Performance Specification	Requirement	Measured
Minimum Speed	1 mph	1 mph
Maximum Speed	5 mph	5 mph
Approach Angle	20% Grade	30% Grade
Ground Clearance	No Requirement	4 inches
Maximum Torque	No Requirement	16.95 Nm per motor
Battery Life	No Requirement	8 hours
Emergency Stop	100 feet	500 feet
Obstacle Detection	Yes	Yes, 6 feet
Line Following	Yes	Yes

Table 2: Performance specification requirements and measured performance

In addition to testing the electrical and software components of the IGV, the mechanical aspects of the IGV were also assessed. A payload was constructed based on the IGV requirements, along with a practice 30 percent grade ramp to test the mechanical features. The characteristics of the platform were observed on uneven and grassy terrain to verify performance. These measured performance characteristics are shown in Table 2.

Performance to Date

At this time, the Roger Williams University IGV navigates to a given waypoint, avoids obstacles, and remains within the lines. Although the IGV is performing within specifications, testing and debugging is ongoing to reduce processing time and improve the platform's performance. Current efforts are focused on improving the processing speed to ensure a minimum speed of one mile per hour average is achieved while staying within the course.

Future Considerations

Although the IGV platform meets qualifications and will be competing in the Basic Autonomous Navigation Course, there are a few modifications that could be made to improve the vehicle's performance in the coming years. Mechanically, the team made significant modifications to the LIDAR design; however, improvements could still be made to prevent the LIDAR from overheating and improve the speed of the LIDAR sweep. One of the electrical improvements would be to upgrade the sensors and microcontrollers, which was not a possibility this year due to budget and time constraints. Battery life was also an issue during testing, and although the added battery monitors are helpful in assessing voltage, the batteries still drain fairly quickly. It would be beneficial for next year's team to improve the battery life by reassessing the connected subsystems and the power they draw. In addition, the software currently does not include a localization and mapping component with path planning, which would be useful for successful completion of the more advanced courses and should be considered for next year's IGV team.

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