IGVC2014-ISAIAH

ISAIAH: AN IGVC ROBOT

Bob Jones University

Brandon Allweil, Timothy Anglea, Rich Armstrong, Alexander Carnahan, Lauriana Cojocaru, Jared Guyaux, Gideon Messer, Brandon Michaud, Charles Middlebrook, Jeremiah Perez, Sam Plyler, Joshua Spofford, Simon Vancina, John Wiser

John C. Hawkins, M.S., Jchawkin@bju.edu

William P. Lovegrove, Ph.D., blovegro@bju.edu

INTRODUCTION

Isaiah is a differential steering, 3-wheeled robot designed to compete in the 22nd annual Intelligent Ground Vehicle Competition. This innovative robot is a significant improvement over previous BJU entries.

DESIGN PROCESS

Isaiah was developed to meet the requirements of IGVC for the Auto-Nav challenge, and to be stable at the maximum speed of 10 mph. It was constrained by budget limits, a maximum weight, and available resources. The team designed an appropriate structure with components that support the robot's movement, control, power, and sensing. The mechanical design model of the robot was developed in SolidWorks, while electrical schematics were created using CadSoft's EAGLE design software. The software systems implemented in Isaiah were developed in National Instruments LabVIEW.

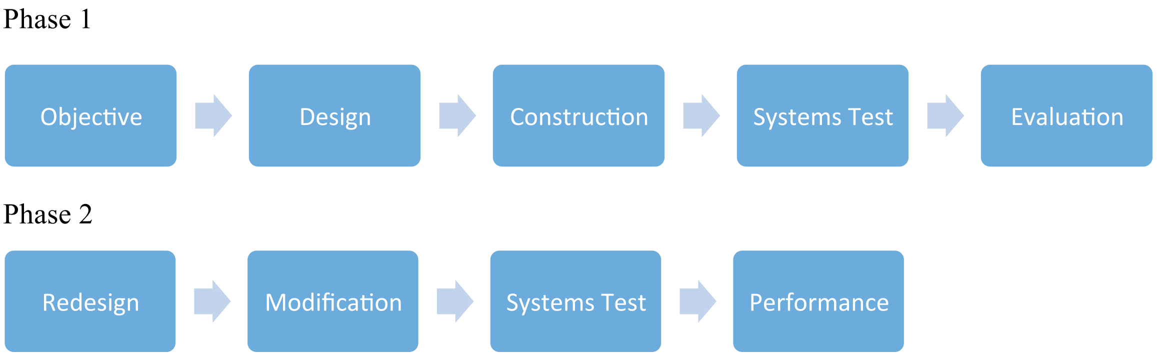

Figure 1: The design process

Development of Isaiah was split into two phases (Figure 1). During phase one, students in the Mechatronics class carried out the initial design and construction. In phase two, during the following semester, a volunteer team of six students fine-tuned the design. The time contribution of each team member is summarized in the Table 1.

Names of Members	Academic Department and Class	Phase	Person-hours expended
Brandon Allweil	Engineering, Senior	1, 2	160
Timothy Anglea	Engineering, Junior	2	30
Rich Armstrong	Engineering, Senior	1	60
Alex Carnahan	Engineering, Senior	1, 2	300
Lauriana Cojocaru	Engineering, Junior	2	55
Jared Guyaux	Engineering, Senior	1	60
Gideon Messer	Engineering, Senior	1	60

Brandon Michaud	Engineering, Senior	1	40
Charles Middlebrook	Engineering, Senior	1	30
Jeremiah Perez	Engineering, Senior	1	60
Sam Plyler	Engineering, Senior	1	30
Joshua Spofford	Engineering, Senior	1, 2	240
Simon Vancina	Engineering, Senior	1, 2	230
John Wiser	Engineering, Senior	1	65
Total			**1421**

Table 1: Hours spent per person

INNOVATIONS

Isaiah contains the following innovative features, each described in detail in its respective section.

Hybrid Power

A generator-based hybrid power system provides up to 8 hours of run time. Isaiah can operate on batteries alone for 30 minutes. The generator can recharge the batteries while also powering the robot.

Single Camera Stereo Vision

The stereo vision system uses a single camera with an innovative mirror array to produce a stereo image pair for distance measurements.

Suspension

The robot has a driven axle suspension system that reduces vibrations throughout the frame, steadying sensors and lessening wear on the robot.

Stowable Mast

The chassis includes a lay-down mount for the mast for easy transportation.

Short Wheelbase with Tip-Over Protection

Isaiah's short wheelbase allows for high maneuverability, but also creates the danger of tipping during high-speed stops. A tip wheel prevents tipping without lengthening the vehicle.

Software

Advanced software features include shape-recognition filters used to detect lines, haversine distance calculations between waypoints, the A* path planning algorithm, and a sophisticated algorithm for creating an extended list of motor commands from a planned path.

MECHANICAL DESIGN

Isaiah's chassis (Figure 2) was designed for compactness, effective sensor positioning, and easy component accessibility. First, the chassis' 29x40x70in (WxLxH) size makes it easier to navigate the course, and the low volume of empty space ensures that materials are not wasted. We implemented our compact design by using 1-inch framing and unique design solutions, such as storing the batteries in a compartment underneath the main frame. Second, our sensors are positioned for maximum effectiveness. The 6-foot tall mast allows our antennas to receive clear signals, the warning light to remain visible from all sides, and the line camera to have a clear view of the ground. The forward portions of the chassis allow the LIDAR and stereo camera to effectively scan their surroundings. Third, all necessary components are easily accessible within the frame. For example, the generator easily slides out of the right side of the robot once the retaining bar is raised, and the panel below the payload is hinged for access to the electrical compartment. In addition, electricity gauges are easily readable, and there is easy access to the laptop and control panel.

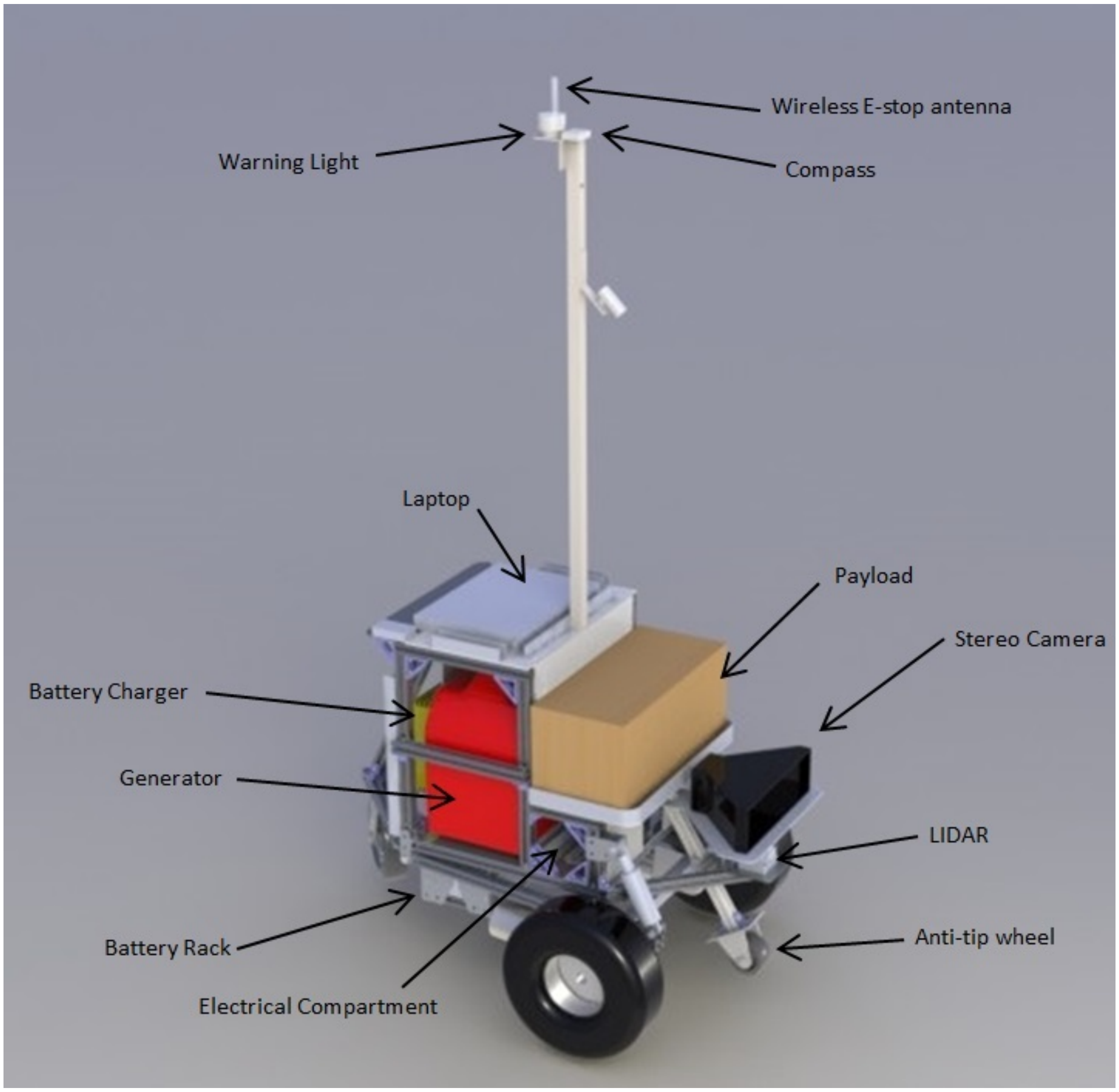

Figure 2: Mechanical design

Suspension

A new element in our design this year is the driven axle suspension system. Our purpose was to reduce vibrations caused by the main drive wheels, making the sensor inputs more reliable, particularly from the LIDAR and cameras. In order to prove that our design was useful, we first conducted an accelerometer test on Isaiah without suspension. After we built the suspension on the new frame, the vibrations of the frame (Figure 3) were noticeably reduced.

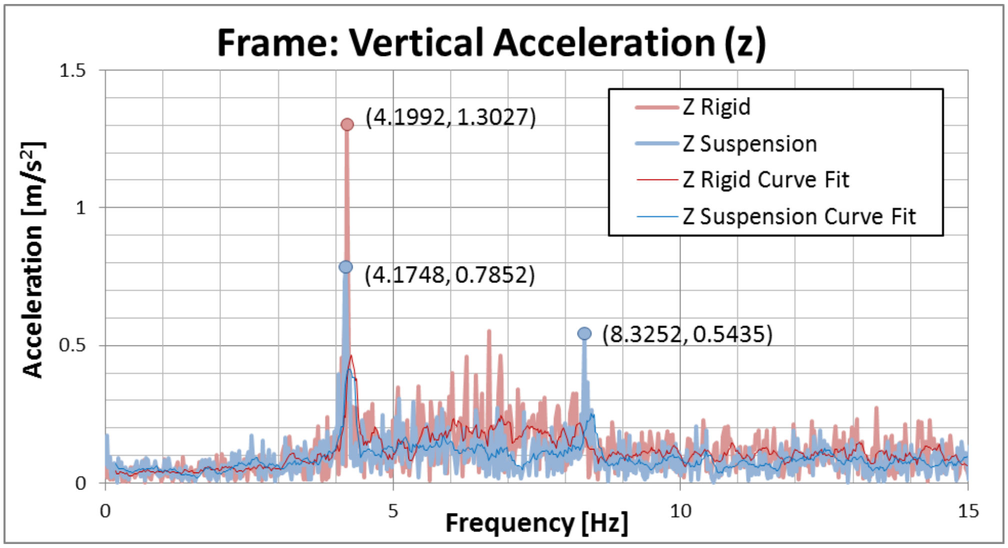

Figure 3: Vertical acceleration vibration data

Anti-tip Wheel

Given the weight, center of gravity, and desired top speed of Isaiah, the mechanical design team decided that an anti-tip wheel was necessary. Our mathematical models determined that if the robot were suddenly stopped without slippage while travelling at the maximum speed of 10 mph, it would pitch forward past its balance point. To avoid this we added an anti-tip wheel two inches above the ground in front of the robot. In the event of the robot pitching forward, the anti-tip wheel will contact the ground, moving the robot's center of gravity farther back along the moment arm and allowing the robot to recover.

ELECTRICAL DESIGN

Overview

There were a couple of main goals when designing the electrical system for Isaiah. First was extending the robot's run time. In the past, BJU robots have run solely on battery power, with run times in the 45-minute range. The Isaiah team wanted to increase that time to at least 4 hours. Also, the team wanted to improve on the wiring from previous designs, making it neater and easier to maintain. To meet these goals, Isaiah uses a hybrid power system consisting of both batteries and a generator, and DIN-rail terminal blocks with wire raceways for wire management.

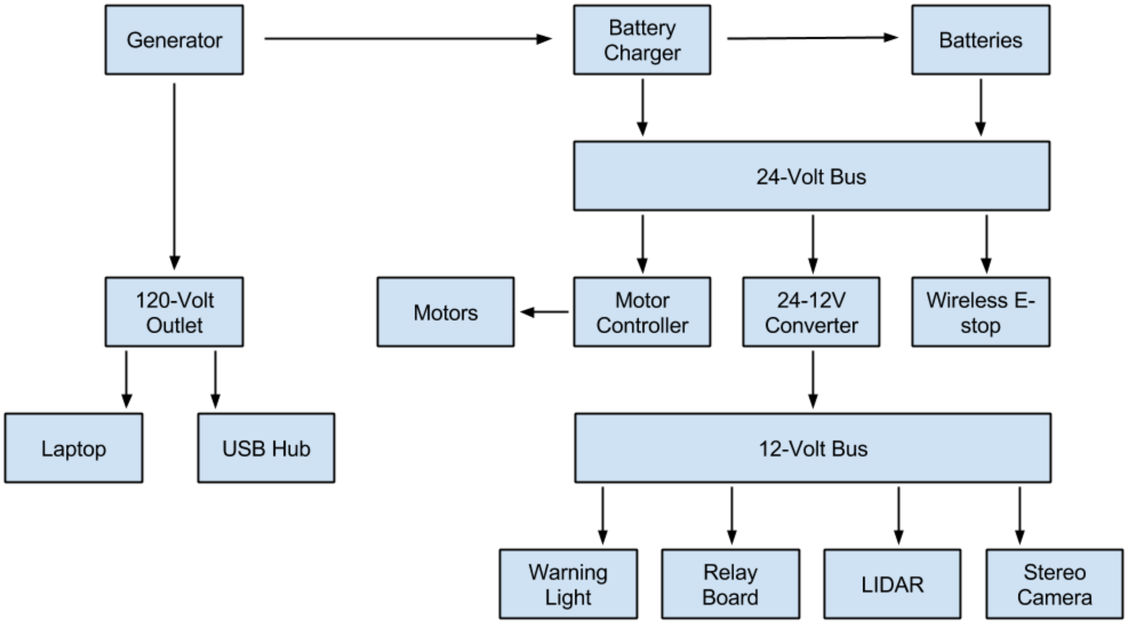

Figure 4: Electrical design

Power Analysis

Previous BJU robots were designed with a dual-voltage system capable of supplying both 24 and 12 volts, and all components ran off one of these two voltages. Since Isaiah uses many of the same components from previous years, we decided to keep the basic dual-voltage design. Calculations indicated that the electrical system would need to supply roughly 20 amps to drive at 4 mph up a 15% slope, expected to be the most demanding steady state.

Generator

Isaiah's power system uses a 1000-watt Honda EU1000i portable inverter generator. A number of characteristics made this generator the best choice. First, it was small enough to make it feasible – the frame was designed around the generator. Second, it was the smallest available generator capable of powering Isaiah. Third, the EU1000i was chosen because it is an inverter generator. Inverter generators produce a much cleaner power signal than regular generators, making them suitable for running sensitive electronic. This allows Isaiah's laptop and USB hub to run off the generator, meaning that all of the robot's components are powered by the same system.

Wiring

In any electrical system with a large number of wires there is potential for messy wiring. To address this problem, wiring connections on Isaiah were made using Wago DIN-rail terminal blocks. The blocks are located in the electronics compartment at the front of the robot, and almost all electrical connections were made there. The wires are routed through slotted wire raceways, keeping them contained out of sight and out of the way. The result is professional-looking wiring that is a major improvement on BJU's previous robots.

Battery Charger

A 24-volt, 15-amp Samlex 2415UL smart battery charger is plugged into the generator. This unit not only float-charges the batteries while the robot is running, but also provides most of the steady-state current for the motors. The charger is key in achieving a long run time, as it significantly slows battery depletion by continuously charging and sharing the current load with the batteries. In addition, it allows the batteries to be charged on board, even if the rest of the system is powered down.

The charger also features overload current-limiting which forms the basis of Isaiah's current load sharing system. While charging the batteries, the charger voltage is higher than that of the batteries. If the motors attempt to draw more current than the 15 amps the charger can provide, current-limiting kicks in and the charger clamps its voltage to the actual battery voltage. The batteries can then supply the balance of the current. Once the overload condition is removed, the charger automatically returns to normal operation.

Motor Controller

The motor controller is a Roboteq AX2550. It features dual-channel motor control, allowing Isaiah to steer by sending different outputs to each of the two main wheels. It also includes the e-stop function used on Isaiah.

Power Converter

To accommodate electrical components that run on 12 volts, Isaiah uses the Pyle Audio PSWNV480 switched-mode power convertor. It converts 24-volt DC into 12-volt DC, and has been used in previous designs. The output is fused at 20 amps to protect Isaiah’s 12-volt components from any unexpected power surge.

SAFETY AND RELIABILITY

E-Stop System

Isaiah’s emergency stop system can be activated in one of two ways: by pressing the red e-stop button in the center of the control panel, or by pressing the button on the e-stop remote. The e-stop remote is a small, black key fob with a single gray button. The remote has been successfully tested to a range of 100 meters.

The emergency stop system takes advantage of the e-stop built into the motor controller. If the e-stop pin is tied to ground, it will disable the controller. Activating the e-stop through either of the two methods will ground this pin, stopping the robot.

The wireless portion of the e-stop system is operated using a HORNET-S1-ND wireless relay from RF Solutions. The HORNET features an antenna that can be separated from the relay unit by a cable. This allows the antenna to be mounted on top of Isaiah’s sensor mast while keeping the relay unit hidden in the electronics compartment.

Pedestrian Safety

Isaiah’s warning light is a yellow Banner Engineering K50 Beacon EZ-Light. This light was chosen because it can be easily seen from all directions, is bright enough to be visible in daylight, and can be powered from Isaiah’s 12-volt power bus. The light is continuously on while the robot is remotely operated, but switches to a blinking pattern when the robot is in autonomous mode. Blinking is achieved using a software-controlled Numato Lab 2-Channel USB Relay Module.

Sharp edges on Isaiah’s frame have been rounded off and padded, to minimize injury or damage in the event of a collision.

Gasoline Safety

Because of the risks inherent in any situation involving gasoline, the team developed an extensive safety policy governing the handling and storage of the generator and its fuel, in compliance with OSHA 1926.152. Gasoline is stored in an approved metal gas can, and the generator is kept in a flammables storage locker when not in use. A vapor cap on the generator keeps fumes from escaping the fuel tank while in storage. The generator is never used while inside buildings, vehicles, or in crowded locations.

When transporting the generator by hand, it is always sealed to prevent the leakage of fuel or fumes. The spark plug is also disconnected when transporting the generator in a vehicle. These requirements are followed to ensure the safety of all, especially those handling the generator.

Electrical Safety

The electrical system was designed to protect both the user and the equipment. Every major component in the circuit is equipped with a fast-acting fuse, and the entire circuit is fused at 30 amps. In addition, covers have been placed over high-current connections that could pose a shock hazard to the user, such as those underneath the control panel.

During operation, and especially when moving over uneven ground, the robot experiences significant vibration. This vibration could potentially damage or interfere with the operation of the laptop's hard-drive. To increase durability and reliability, the laptop's hard disk has been replaced with a solid-state drive.

Isaiah uses UL and DOT-certified sealed lead-acid batteries. These batteries are low-maintenance and can be safely used in any orientation.

EFFICIENCY

Mechanical Efficiency

Mechanically, the robot was designed to be compact with overall dimensions of 29x40x70in (WxLxH). Using a simple bounding box (figure 5) which roughly illustrates our robots footprint, our vehicle has a filled percentage of 26% from the ground up to the top, not including the mast. Eliminating ground clearance and the extra space on the sides, the efficiency of the central chassis is much higher. Included in this design was the use of 1-inch, T-slotted framing (as opposed to the 1.5in T-slot used previously). For most of the panels, we used HDPE plastic, which is lightweight and easily machinable.

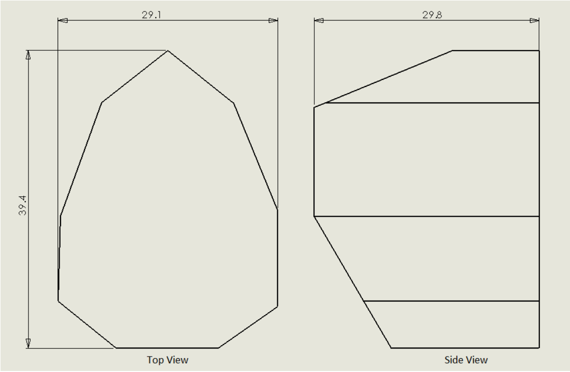

Figure 5: Chassis bounding box

Gasoline engines are typically very inefficient, and we calculated the efficiency of the EU1000i to be roughly 20%. However, gasoline has a very high energy density. The 0.6 gallons of gasoline in the generator's fuel tank carry approximately 70-million joules of energy. This is equivalent to the energy contained in a 1,200-lb lead-acid battery. If only 20% of this, or 14-million joules, is converted into electrical energy, the generator still provides the equivalent energy of a 240-lb battery, while only weighing 33-lbs itself.

Electrical Efficiency

Isaiah's electrical system was designed to be energy efficient. The generator includes a throttling feature which adjusts the speed of the engine according to the demand for power. This greatly increases the efficiency of the engine and the run-time of the entire robot. In addition, the voltage converter is the switched-mode type, providing 85% efficiency.

On top of the power drawn by the motors, the rest of Isaiah's electronics consume roughly 75 watts. As described later in the "Detailed Power Analysis" section, the total steady-state motor power is 272W. Thus, the steady-state power draw for the entire robot is around 350W, of which 20% is consumed by the electronics.

PERFORMANCE

Predicted Performance

Based on the size and angular velocity of the wheels and the motor controller firmware settings, the robot's top speed is predicted to be 8.9 mph. For greater design flexibility, the chassis was built to accommodate the contest maximum speed of 10 mph. At that speed, the robot is predicted to tip forward in the event of a sudden stop, requiring the use of the tip wheel.

The two devices that draw the highest current from the bus are the motors and the LIDAR. At 5 mph on grass, the motors are predicted to draw 11 amps, as detailed below. The LIDAR is rated at 1 amp, maximum. Therefore, the total predicted steady-state current draw is 12 amps.

Different obstacles are detected at different distances, depending on the sensor. The LIDAR is capable of detecting objects at well beyond the 10 meters required by our software, while the line camera can only see 3 meters ahead. The reaction time of the software is predicted to be less than 500 ms. At the predicted top speed of 8.9 mph, the robot travels 2 meters between frames. In this worst-case scenario all sensors still see far enough ahead to avoid collisions.

Our GPS unit uses NDGPS corrections as is theoretically capable of 0.67 meter errors per 100 km from the nearest DGPS station. Oakland University is 50 km from the Detroit DGPS station. Thus, GPS errors are expected to be about 0.33 m.

Detailed Power Analysis

Isaiah's electrical system was designed to comfortably supply enough current to drive the robot at a steady-state speed of 5 mph. To determine the power required to move the robot, we timed how long it took to pull it across a distance of 30 feet on grass, using a gauge to measure the force required. We took a number of data points and calculated power from the following equation:

$$P = \frac{F * x}{t} \tag{1}$$

where P is power, F is the force required to pull the robot, x is the distance it was pulled, and t is the time it took to travel that distance. We used this data to create the chart shown below.

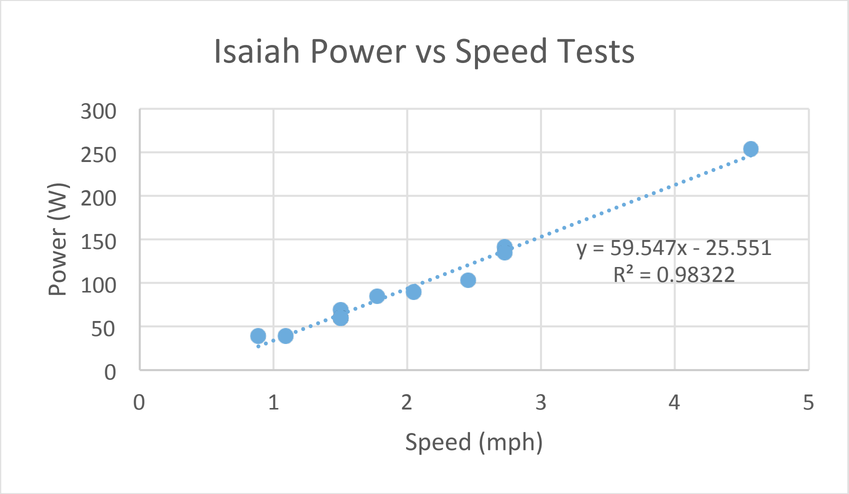

Figure 6: Isaiah power vs speed tests

The trend line is clearly linear, and the equation of that line can be used to calculate the power required to move Isaiah over level grass at any speed. Therefore, at 5 mph the required power is,

$$59.547 * 5 - 25.551 \approx 272\, watts \tag{2}$$

More importantly, however, is the amount of power required to move at this speed up a 15% slope, the maximum incline encountered at IGVC. Isaiah weighs roughly 200 lbs (90.7 kg), so the energy required to raise that mass 15 meters up is

$$mass * acceleration * height = 90.7kg * 9.81\frac{m}{s^2} * 15m = 13{,}346.5\, joules \tag{3}$$

The hypotenuse of the 15% slope is 101.1m long, so at 5 mph (2.24 m/s) it takes 45.1 seconds to travel that distance. Power is then energy over time,

$$\frac{13{,}346.5\, J}{45.1\, s} \approx 296\, watts \tag{4}$$

Adding this to the 272 W required to move over flat grass, we find it requires roughly 568 W to travel at 5 mph up a 15% slope.

Actual Performance

While running on level grass at 5 mph, Isaiah draws 11 amps of current. The batteries are ideally 24 volts, but sag to 23 volts under that load. The power consumption is then $23V * 11A = 253\, W$, which is close to the theoretical value of 272 W. We also climbed a 17% slope at 3.9 mph and measured a 30 amps draw. Theoretically, the current draw should have been 21 amps, or 26 amps including voltage sag and system inefficiencies.

Upon testing, the robot did tip while attempting an abrupt stop from 10 mph. In subsequent tests, the anti-tip wheel contacted the ground as designed and prevented the robot from tipping over. To verify our speed calculations we set the motor controller's speed to a theoretical 3.9 mph and we measured Isaiah's actual speed to be 3.6 mph.

In testing the LIDAR successfully detected obstacles at the expected range of 10 meters. The camera was also confirmed to work at 2.8 meters from the robot.

SENSORS AND ACTUATORS

Line Detection Camera

The Microsoft LifeCam Cinema gives Isaiah a reliable, compact camera input with a wide field of view and sufficient image quality to detect lines. We determined the camera's viewing angle based on the software team's map size, maximizing the coverage of their mapped area.

LIDAR

In order to allow for increased accuracy in sensing the depth of obstacles in Isaiah's path, we have included a Hoyuko UTM-30LX LIDAR scanning laser sensor. This sensor sweeps a laser across a 180° arc to detect reflections off of obstacles up to 30 meters away.

Stereo Camera

One of our most innovative design features this year is the addition of the single-camera stereo vision system. This camera is different from the line camera in that it uses a complex mirror design in order to obtain dual vision. This dual vision comes from four mirrors: two smaller inner mirrors right next to the camera and two larger outer mirrors facing outward from Isaiah. The camera and inner mirrors are rotated at a slight angle in order to align the optical axes of the top view and bottom view. We chose the industrial Unibrain Fire-i Digital Camera as our sensor because of its small size and high frame rate.

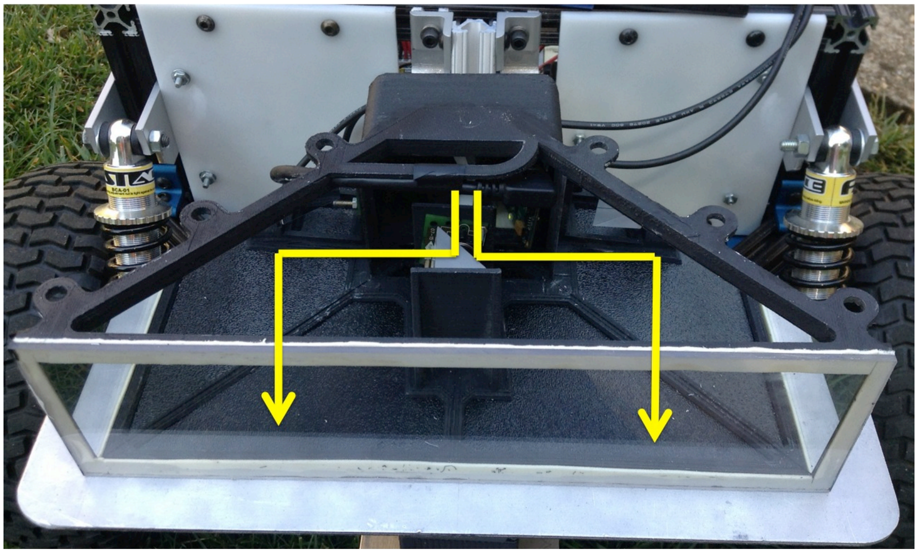

Figure 6: Stereo camera design (light path shown in yellow)

Figure 7: View from stereo camera

SOFTWARE STRATEGY

The software systems implemented in Isaiah's design were developed in National Instruments LabVIEW. LabVIEW is a visual programming language that makes use of a unique dataflow design structure. LabVIEW also contains a large library of subroutines related to instrument interfacing, data acquisition, mathematics, and automation, allowing for rapid software development. This library includes UDP packet processing suitable for handling JAUS messages.

Graphical Programming

Programs written in LabVIEW, called VIs (virtual instruments), are divided into two sections: a front panel and a block diagram. The front panel is a GUI interface that is used to display and manipulate system variables. Debugging is greatly accelerated by this useful feature because input variables can easily be altered by the user, even while the program is running, and output variables can be displayed through a diverse range of methods like graphs, tables, or pictures with just a few clicks of the mouse. The block diagram contains the functional part of the program. Instead of writing lines of code, LabVIEW allows a developer to quickly create complicated programs by inserting functions and operators with an innovative drag-and-drop approach. The block diagram also assists in debugging by allowing the developer to watch the program in a signal-flow format, which presents what is happening in an easy-to-understand way that simply stepping through code line-by-line never could.

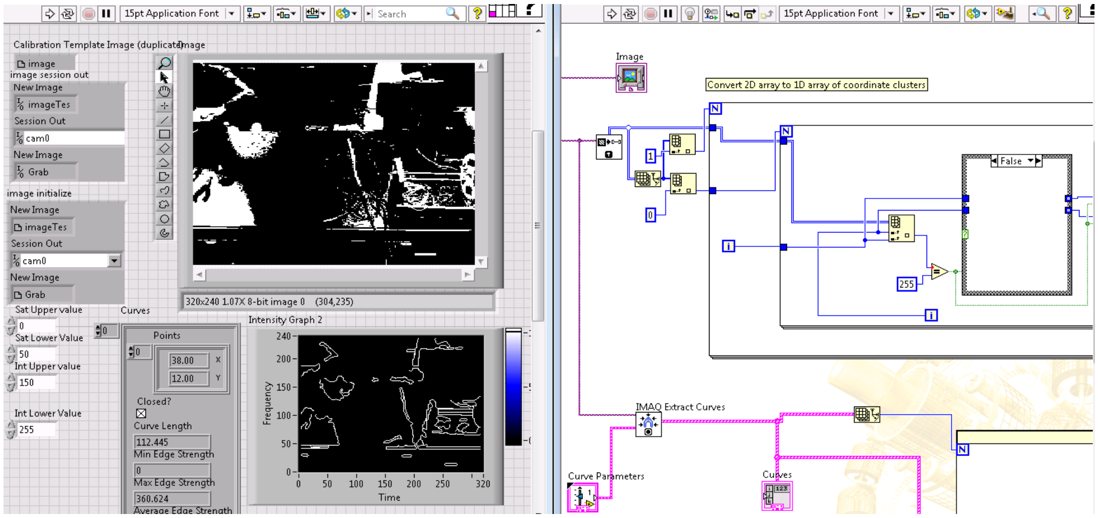

image: image

New Image: imageTes

Session Out: cam0

New Image: Grab

New Image: imageTes

Session Out: cam0

New Image: Grab

320x240 1.07X 8-bit image 0 (304,235)

Sat Upper value: 0

Sat Lower Value: 50

Int Upper value: 150

Int Lower Value: 255

X: 38.00

Y: 12.00

Closed? ☒

Curve Length: 112.445

Min Edge Strength: 0

Max Edge Strength: 360.624

Average Edge Strength

Figure 8. A LabVIEW front panel and block diagram.

Modularity

LabVIEW makes code re-use and modularization simple with the use of sub-VIs. After a developer has completed a VI, he can assign variables from the front panel as inputs and outputs for the VI. At this point, any new VI is capable of accessing the old one simply by dragging a box that represents that VI into the new VI's block diagram. The use of sub-VIs in a program allows programs to remain relatively simple while implementing very large and complicated ideas.

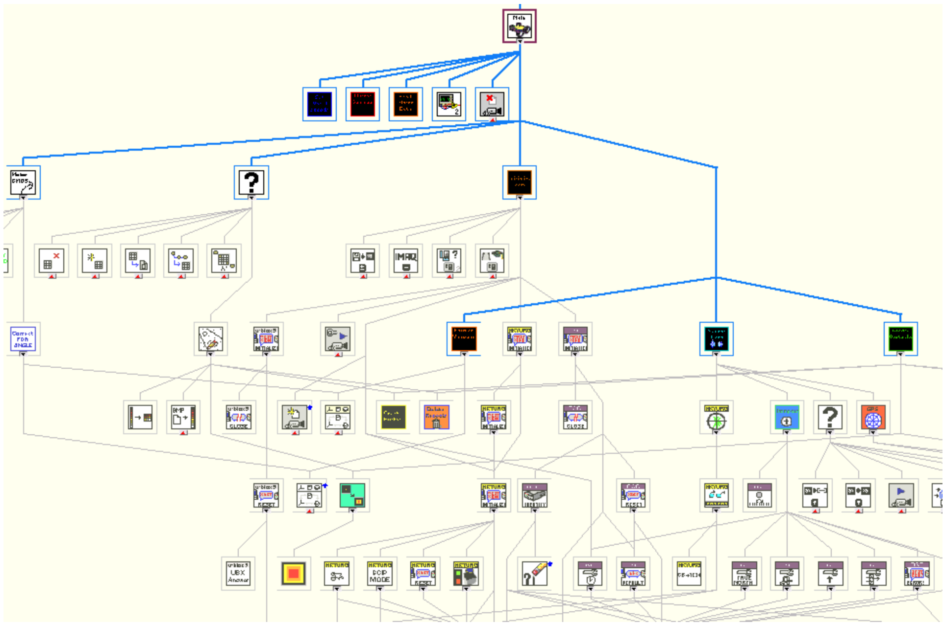

Figure 9. The VI hierarchy for Isaiah's main program.

Parallel Loop Design Pattern

Isaiah's main program uses two concurrently-running, continuous loops; the first gathers sensor data, processes the data, and creates a set of commands for the motor controller, and the second sends that data to the motor controller at timed intervals. The use of parallel loops in LabVIEW automatically allows us to take advantage of our laptop's dual-core processor through multithreading.

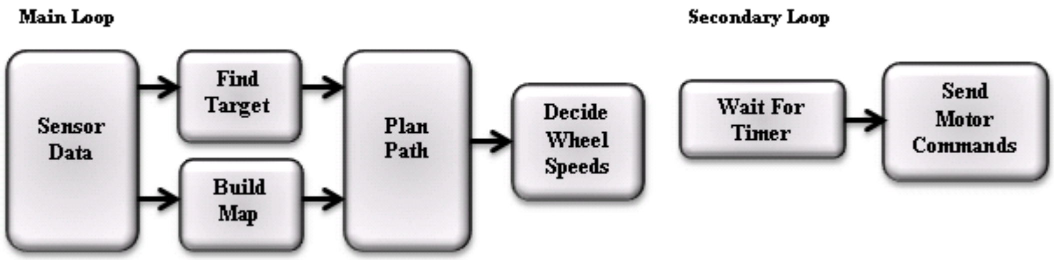

Figure 10. Isaiah's top-level design pattern.

MAPPING TECHNIQUE

Obstacle Detection

The LIDAR scans the area in front of Isaiah and returns an array of the distances to the nearest obstacle in every direction. This array is easily translated into a physical map of obstacles.

Line Detection

After Isaiah receives an image from the camera, it sends the image through a hue saturation luminance (HSL) threshold filter. Using the saturation and luminance values, Isaiah can filter for both brightness and color. At this point, the image contains only the points that are white in the original image. However, on sunny days many objects reflect brightly enough to make it through the threshold filter, creating a noisy image. To deal with this problem, we use shape recognition algorithms that can limit the minimum size of what are supposed to be white lines. In order to translate the lines to Isaiah's map, we correct the image for camera distortion using conversion info that we obtained by experimentation and calculation.

Figure 11a: Line-camera view

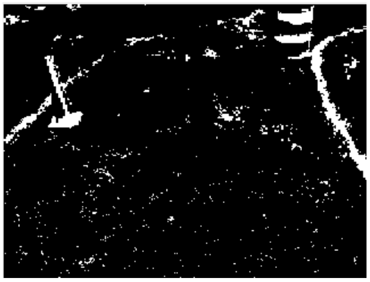

Figure 11b: Threshold filter

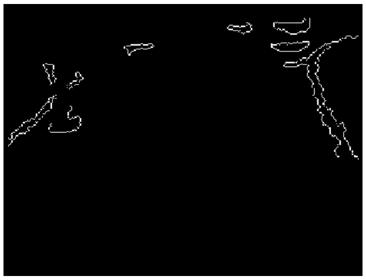

Figure 11c: Shape filter

SYSTEMS INTEGRATION

Global Target Direction

Using the GPS, we obtain a vector from Isaiah's position to the next waypoint. If the waypoint is not located close enough to Isaiah, the point that intersects the vector on the edge of Isaiah's map becomes the target point. If Isaiah is very close to the waypoint, drive speeds are decreased to improve the approach. When Isaiah is within one meter of the target waypoint, the next waypoint is selected as the new target.

Forced Forward Movement

For obstacles that are more complex than just following a path, such as switchbacks and dead ends, we added a border of obstacles around the bottom, left, and right edges of the relative map. Around the entire image is a single-pixel border of white space that allows the path planning to navigate to the GPS point without going through obstacles. Since Isaiah is incapable of driving backwards, adding these fake obstacles keeps the robot from getting stuck in situations where the relative GPS coordinate is behind the robot.

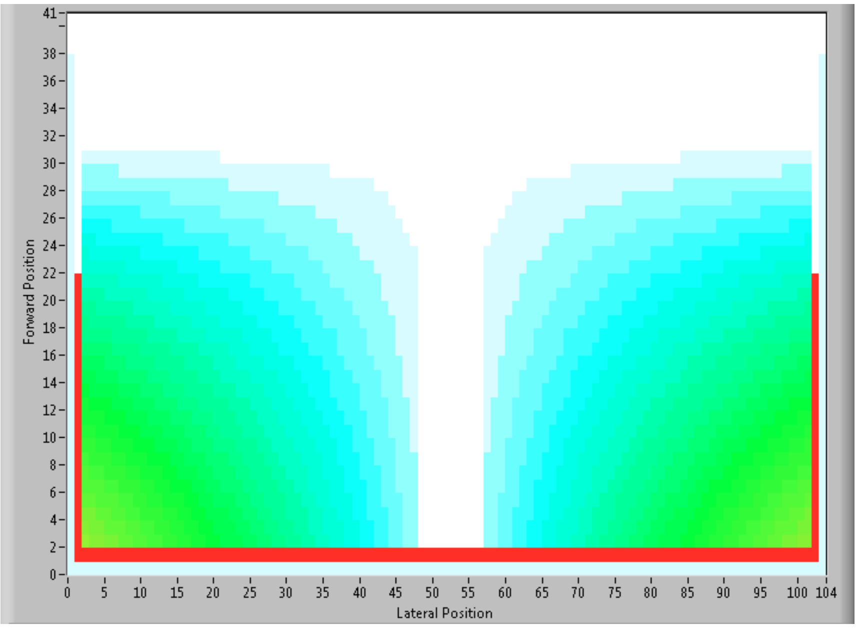

Figure 11. Sloped map in blue and green, with map border in red.

Weighted Obstacles/Directions

In order to account for the fact that Isaiah's path planning treats the robot as a single point on the map, we expanded all obstacles on the map by a radius equal to a little over one-half Isaiah's width. We also added layers of progressively less resistance around each obstacle to encourage the path planning to stay farther away from obstacles if possible.

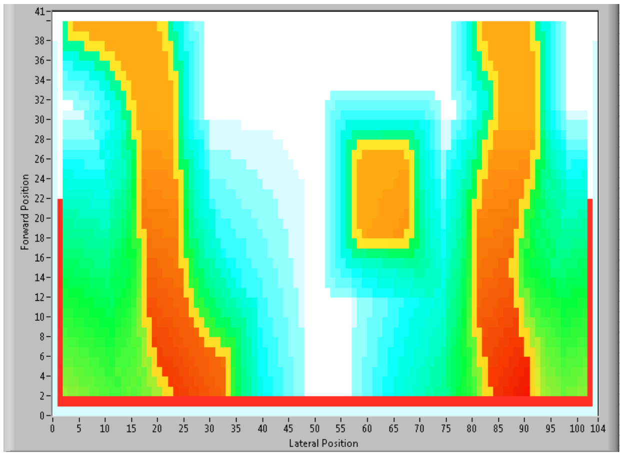

Figure 12. Expanded obstacles in red with progressive resistance in yellow, green, and blue.

Least Resistance Path Planning

Isaiah implements an A* search algorithm on the obstacle map to create a least-cost path from its current position to the target position. This method allows for an easy way of not only avoiding obstacles but also avoiding areas near obstacles.

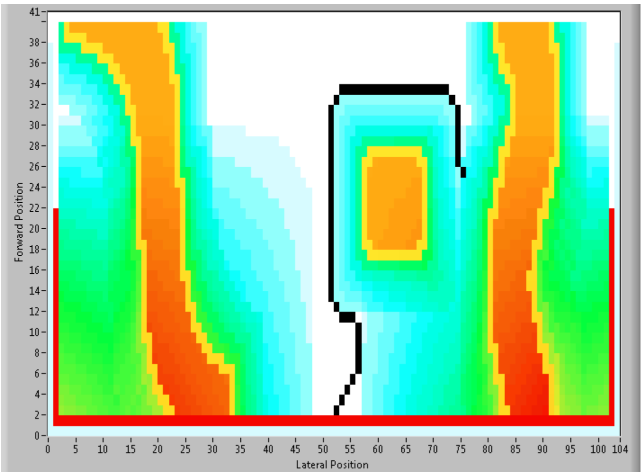

Figure 13. A* algorithm path.

Accurate Motor Commands

Isaiah is designed to be able to follow the path created by the A* algorithm with a high level of accuracy. Because the algorithm creates paths with sharp corners, and because Isaiah usually attempts to run at a constant velocity, accurate path-following was not easy to achieve. Early attempts involving a single circular curve over a short part of the planned path were too inaccurate in many situations. To improve this, we developed our own algorithms to generate a list of evenly-spaced motor commands by creating a continuous curve of equal-length arcs that attempt to conform to the planned path.

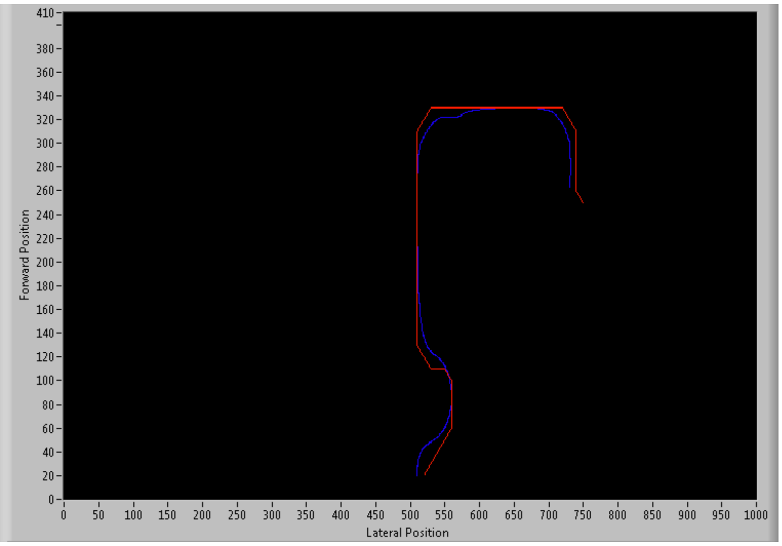

Figure 14. Planned path (red) and predicted actual path (blue)

COST ESTIMATE

	Market Cost ($)	Team Cost ($)
Chassis Materials	1,046.58	1,046.58
Electrical Components	7,918.20	7,918.20
Generator	800.00	800.00
Sensors	659.68	659.68
LIDAR	5,590.00	0.00
Motors	570.00	570.00
Computer	500.00	500.00
Miscellaneous	29.26	29.26
Stereo Camera	328.00	328.00
Total	17,113.72	11,523.72

Table 2: Cost estimate

CONCLUSION

Isaiah successfully integrates a number of innovations into a vehicle ready to compete at IGVC. Mechanically, our compact, accessible, and efficient design is a stable and maneuverable platform for an autonomous vehicle. Our sensors have seen significant innovation with the single camera stereo vision, as well as having tried and true methods such as our LIDAR. The software also has a number of innovative features for path planning and obstacle detection. Put together, our mechanical, sensor, and software designs will enable us to navigate through the IGVC course.