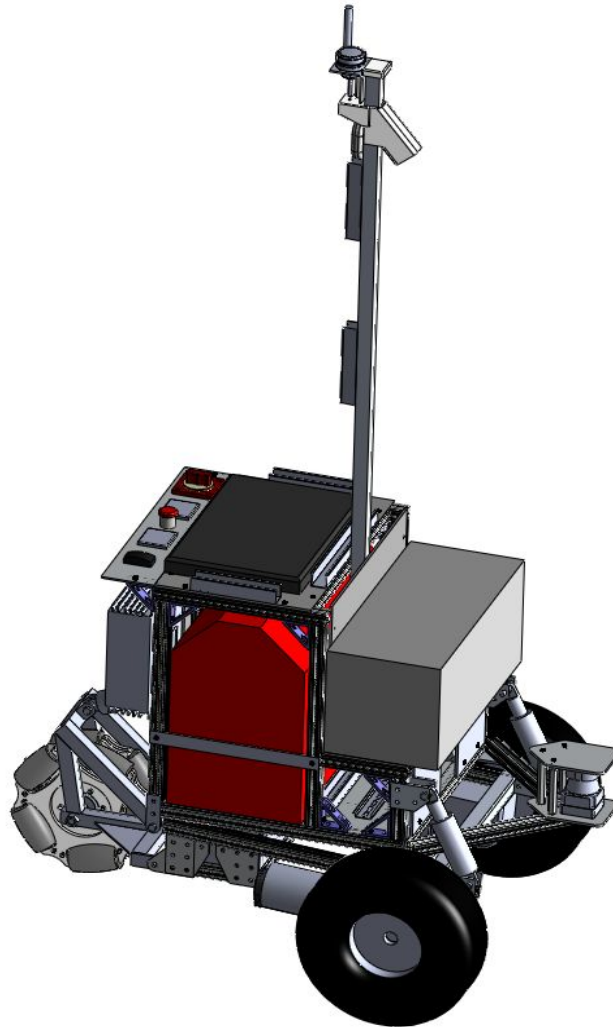**KEZIA: AN IGVC ROBOT**

Bob Jones University
May 15, 2016

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(See attached statement of integrity)

Introduction

Kezia is an autonomous ground vehicle designed to compete in the 24th Intelligent Ground Vehicle Competition (IGVC). Featuring a complete software overhaul and a greatly enhanced suspension system, Kezia promises to be a significant improvement over its predecessors.

Organization

The Fall 2015 Mechatronics class worked on improving the already existing robot. The class was divided into four sub-teams: Situational Awareness, Mechanical Upgrades, Auto-Navigation, and Design Integration. The rear suspension upgrade was completed during this semester. During Spring 2016, a five person extra-curricular Robot Team was formed. This team worked on the new robot body design, upgraded the GPS navigation and image processing software, and developed a new fuzzy logic based algorithm. The contribution made by students in both semesters is outlined in Table 1.

Table 1. Student Contribution

Names of Members	Academic Department and Class	Phase	Hours Invested
Noah Dargy	Engineering, Senior	1	64
Adam Distad	Engineering, Senior	1	112.5
Stephen Jones	Engineering, Senior	1,2	222
Sam Koenke	Engineering, Senior	1,2	200
Nathan Larson	Engineering, Senior	1	82.5
Evelyn Licona	Engineering, Senior	2	80
Daniel Marinelli	Engineering, Senior	1,2	170
James Reynolds	Engineering, Senior	1	88.5
Dillon Rowe	Engineering, Senior	1	55
Alfredo Trujillo	Engineering, Senior	1	25
Andrew Tung	Engineering, Senior	1	84
Nathaniel Woehr	Engineering, Senior	2	80
Caleb Wright	Engineering, Senior	1	75

Design Process

Kezia was designed, using a modified TIDEE process, Figure 1, to meet the requirements of IGVC for the Auto-Nav competition, and to be stable at the maximum speed of 5 mph. The project was constrained by budget limits, IGVC competition rules, and available time. The team evaluated the inherited structure and components that support the robot's movement, control, power, and sensing using a weighted decision matrix. 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 Kezia were developed in National Instruments LabVIEW.
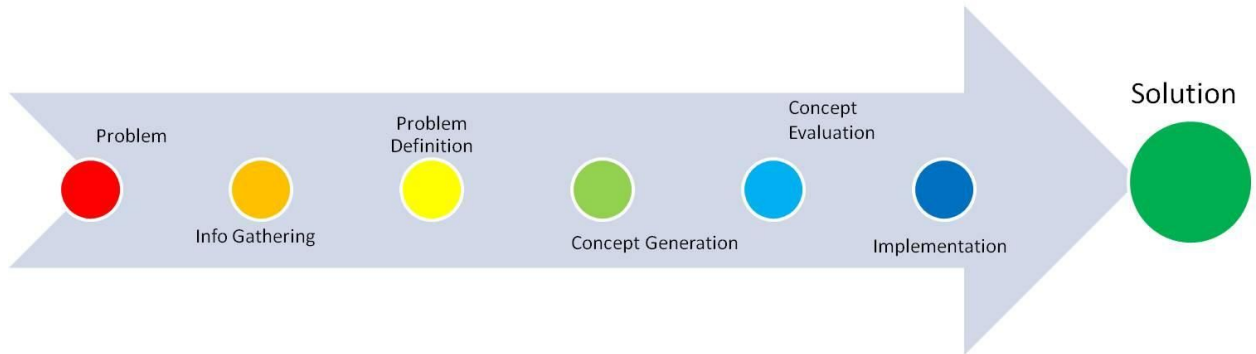

Figure 1. TIDEE Design Process

System Design Overview

Kezia is a combination of the following components, as shown in Figure 2. These components work together as a system to achieve the desired goal of autonomous navigation.
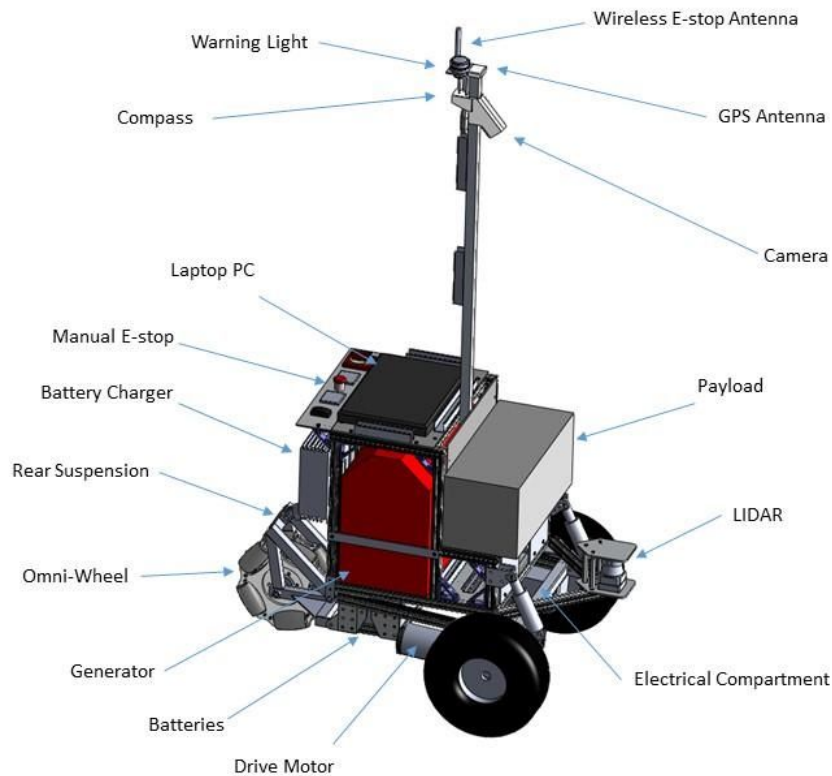

Figure 2. Kezia Subsystem Diagram (body removed)

Design Innovations

Kezia contains the following new features, each described in detail in its respective section.

- **Rear Suspension**
    - The robot has new independent rear suspension with a rigid, lightweight, aluminum trailing arm and coil-over shock absorber to reduce sharp jolts and vibrations.
- **Robot Body**
    - Our robot body design is the result of our first attempt to develop a streamlined body design and fabrication process for future robots.
- **Control Software**
    - Improved the GPS navigation software.
    - Developed a new fuzzy logic based path planning algorithm.
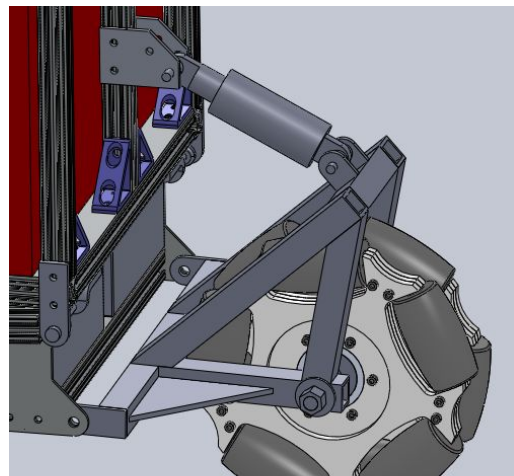   - Improved the image processing software.

Mechanical Design

Overview

Kezia is constructed primarily out of aluminum extrusion bars and square tubing. The new rear suspension system is made of 1" square tubing, 3/16" aluminum plating for the connection points, and ⅛" plating for structural support. This allows for a smaller package while still maintaining structural integrity. Kezia is dimensioned very close to the minimum size requirements in the x and y directions. Most of the robot's mass sits very close to the ground, while the stowable mast extends to the maximum permitted length in the z-direction. These design features allow for a low center of gravity while still allowing for the best possible camera view for navigation.

Rear Suspension

In a previous design we had a rigidly mounted rear omni-wheel. Although this design worked, we wanted to reduce the shock loading into the robot by upgrading to an independent rear suspension. Our goal was to protect components from damage by reducing jolts and vibrations throughout the robot, using a hinged trailing arm and coil-over shock absorber as shown in Figure 3.

Throughout our design process, we discussed attaching our suspension to several different locations on the robot. We found that the suspension would have a better damping effect the lower we attached it. The lowest pre-existing attachable point was the battery rack. We also found that the best design required that both of the spring's points of attachment lie on an arc with its center at the suspension's pivotal point of rotation. This

Figure 3. Rear Suspension

prevented the possibility of extending and compressing the wheelbase as the robot rolled over bumps and holes, while also directing as much force through the spring as possible. In the previous generation of

Kezia, there was no place for us to mount the upper portion of the suspension. As can be seen in Figure 2, we also installed a new extrusion bar in the rear and center of the chassis.

To demonstrate that our design was successful, we performed a series of drop tests to measure the shock loading at the laptop mounting point before and after the suspension upgrade. The results of these tests show that the independent rear suspension was effective at reducing average peak acceleration under drop test loading by 73% as shown in figures 4 and 5.
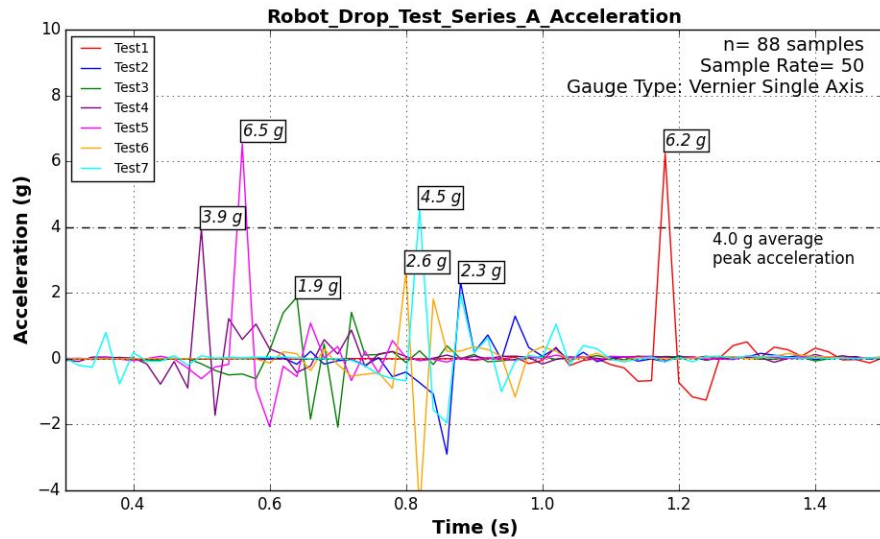
Figure 4. Drop Tests Results From Rigid Rear Suspension
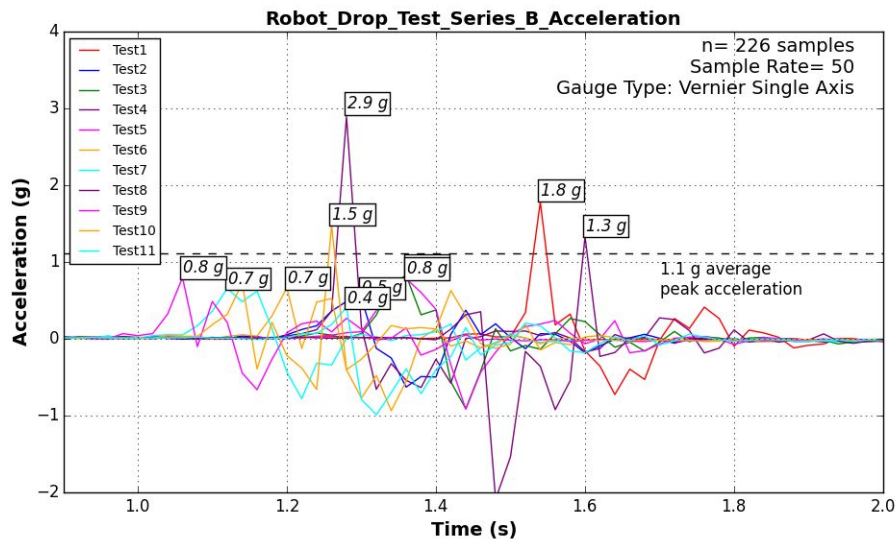

Figure 5. Drop Tests Results From Upgraded Rear Suspension with Shock Absorption

Robot Body

The robot body was made out of 1/8" ABS plastic. The body panels were cut with CNC precision to the shape specified in the CAD model. Though most of the panels now permanently remain on the robot, the panels are secured using a high strength Velcro so that they can be quickly removed.

Additionally, we added a removable panel on the right side for easy generator installation and a small hole on the left panel for the generator exhaust. The front panel was constructed from three pieces and then heated to attain the desired curvature. All curved seams were bonded using fiberglass cloth and epoxy resin. This new body design provides protection Kezia's components from certain weather conditions and provides a more appealing curved appearance.
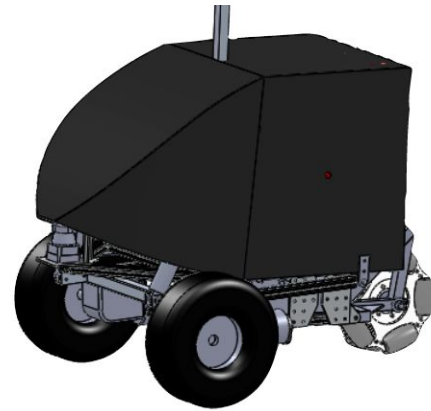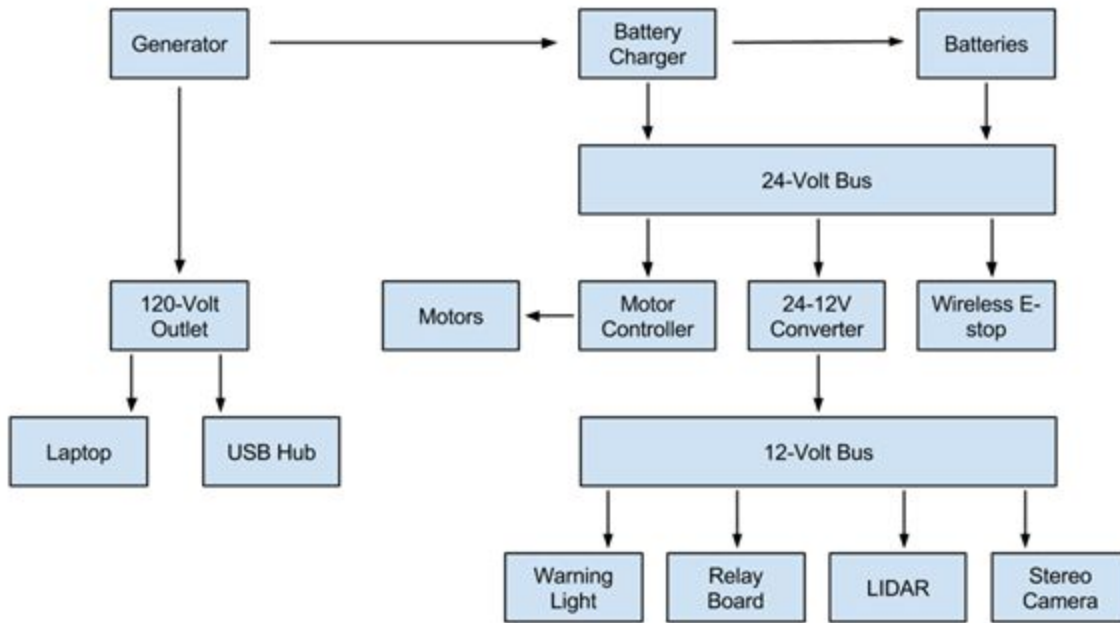

Figure 6. Kezia Body Design

Electrical Design
Overview

Kezia uses a hybrid power system consisting of both batteries and a generator, and DIN-rail terminal blocks with wire raceways for wire management. Additionally updated wire schematics and a wire identification system were added.

Figure 7. Electrical Design

Power Analysis

Previous BJU robots were designed with a dual-voltage system capable of supplying both 12 and 24 volts, and all components ran off one of these two voltages. Since Kezia uses many of the same components from previous years, we decided to keep the basic dual-voltage design. Calculations indicate that the electrical system would need to supply roughly 20 amps to drive at the max steady-state running conditions of 4 MPH on a 15% grade.

Generator

Kezia'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 Kezia. 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 electronics. This allows Kezia'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 Kezia 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 to BJU's previous robots. To easily identify the purpose of each wire, every wire was labeled with the corresponding function name. The function name also correlates with the electric wiring schematic.

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 Kezia'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 AX2850. It features dual-channel motor control, allowing Kezia to steer by sending different outputs to each of the two main wheels. The setting Kezia employs is closed loop separate speed control. The motor controller also includes the e-stop function used on Kezia.

Power Converter

To accommodate electrical components that run on 12 volts, Kezia uses the Pyle Audio PSWNV480 switched-mode power converter. 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 Kezia's 12-volt components from any unexpected power surge.

Situational Awareness Design

Lidar

In order to allow for increased accuracy in sensing the depth of obstacles in Kezia's path, we have included a Hoyuko UTM-30LX LIDAR scanning laser sensor. This sensor sweeps a laser across a 270° arc at rate of 40Hz to detect reflections off of obstacles up to 30 meters away.

Camera

The Microsoft LifeCam Cinema gives Kezia a reliable, compact camera input with a wide field of view and sufficient image quality to detect lines and flags. We moved the location of the camera higher up on the mast in order to increase the distance we could see, while at the same time not creating blind spots at the front of Kezia.

Auto-Navigation Design

Hardware

Kezia's movements are enabled by a National Power Chair R81 series motor attached to each of the front wheels, through a worm driven gearbox. The motors are controlled by a RoboteQ AX2850 Motor Controller set to closed loop separate control. The combined power draw of the motors is approximately in the range of 270-300 watts.

Software

The software systems implemented in Kezia's design were developed in National Instruments LabVIEW. LabVIEW is a visual programming language that makes use of a unique dataflow design structure. Labview was used for all data manipulation, obstacle detection, waypoint navigation, and obstacle avoidance. An overview of the navigation algorithm is given below.
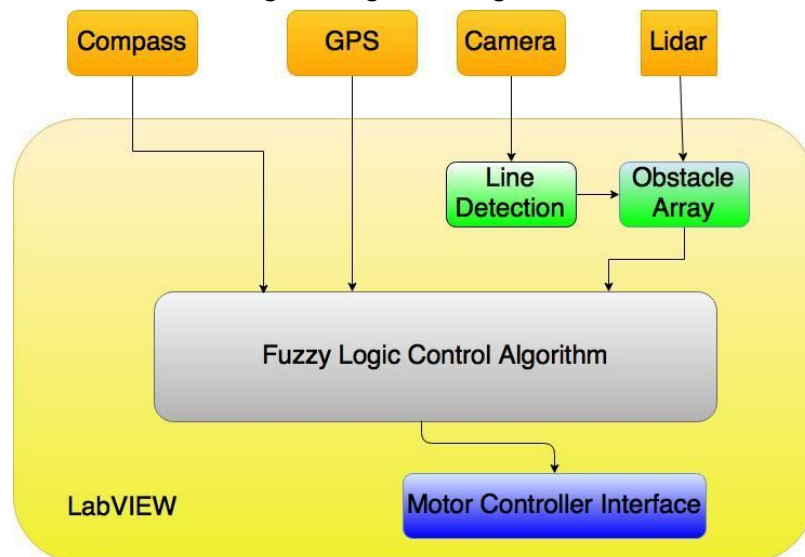
Figure 8. Complete Navigation System

Navigation Strategy

Mapping Strategy

Before Kezia can navigate, it must be able to utilize the data from the sensors. The end result of both the LIDAR and the camera algorithms is an array of object points in polar form that have been sorted to include only the closest point for any given angle. The mapping is laid out here as Kezia sees it with 90 degrees being straight in front.
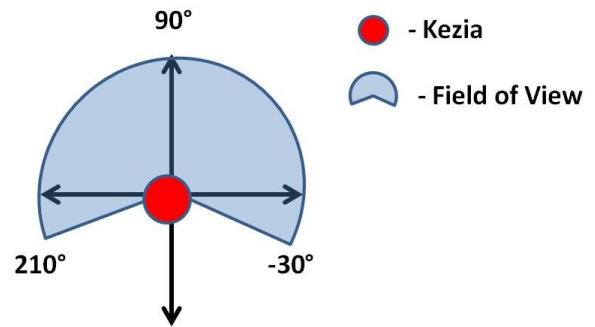

Figure 9. Field Mapping

Obstacle Detection

Kezia detects obstacles using a Hokuyo LIDAR. The scan range is set to only cover 240 degrees to prevent Kezia's front suspensions from registering as obstacles with 90 degrees being the angle directly ahead of the robot. The obstacles are represented as an array of obstacle points in polar form along with the obstacle points representing the lane lines and then sent to the control algorithm as a single sorted array of obstacle points.

Line Detection

Kezia's line detection is the result of two algorithms and represents lines as an array of points in polar form. First, Kezia processes images to extract the lines. Then Kezia maps the pixel locations through two conversion equations into the equivalent real-world plan view location of those object points.

For line extraction, Kezia goes through a series of extraction steps as shown in the example figure below - image cropping, gray-scale with low-pass filtering, mixed-channel thresholding, particle removal, and edge detection. First it crops the bottom of the raw image to prevent the robot nose from reflecting sunlight to the camera and appearing as a lane obstacle (this could occur at certain angles of sunlight due to the

Figure 10. Image processing sequence and final mapped obstacle points

reflectivity of the black plastic).Next, Kezia performs a custom implementation of mixed channel low-pass gray-scale. We found that the blue components of a gray-scaled rgb image show the most contrast between grass and lane lines. To harness this observation, we next gray-scale the image. Then we

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send the image through a low-pass filter to blur noise particles from white to gray. Then Kezia thresholds only based on the blue components of the pixels. Pixels below Kezia's defined threshold are set to black and above are set to white. This step is the most critical because we found a simple grayscale with a threshold accounting for all color components (even when not all thresholds are equal) is not enough for the noise reduction needed for the fuzzy logic control algorithm. After thresholding, the image goes through a particle removal filter. And the final step is edge extraction.

Figure 11. Thresholding based on blue pixel values only

After obtaining an array of white pixels from the final binary image, Kezia must map the pixel locations through two equations into the plan view coordinates relative to the front of Kezia. One equation translates the rows into y-axis locations and the other translates columns into x-axis locations. The y-axis location depends only on the pixel row location and is quadratic in nature. However, the x-axis location depends on both the column and row because of the skewing of the camera image. We used a trigonometric function to account for both variables and map into plan view. The final step is a simple conversion of the (x,y) coordinates into polar form and insertion into the obstacle point array.

Figure 12. Pixel Mapping to Plan View
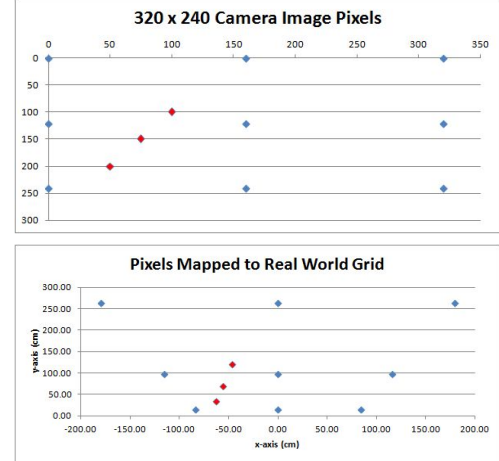
Path Planning Strategy

Kezia employs a custom designed fuzzy logic control algorithm that operates six linguistic variables. The first four linguistic variables are the system inputs. These given crisp inputs of obstacle distance, obstacle angle, waypoint distance, and waypoint angle are fuzzified through chosen membership functions. The remaining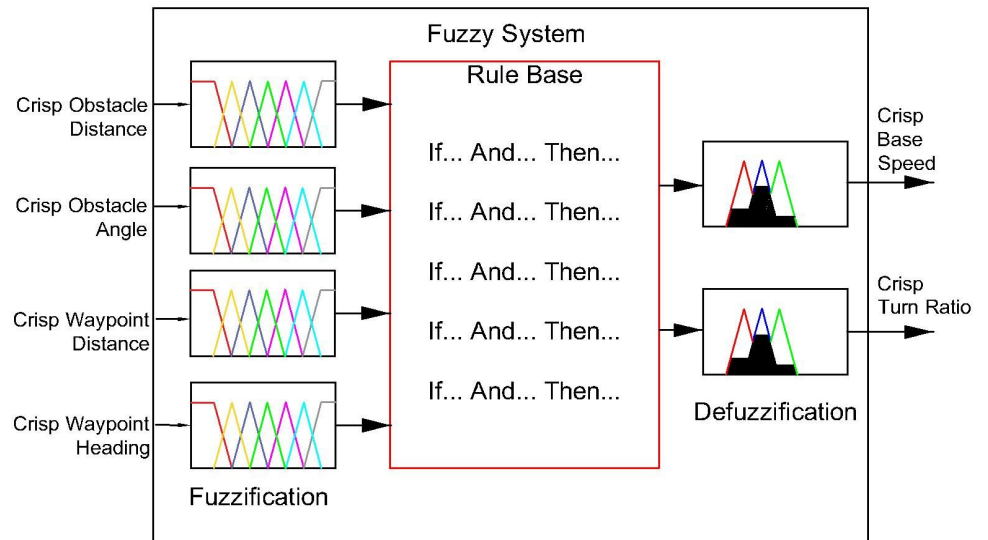 linguistic variables are outputs and are inferred from the rule base and then defuzzified using the Center of Sums method. The crisp outputs are the base speed and base turn ratio.

Figure 13. Fuzzy Control Overview

The overview of Kezia's fuzzy control system is shown in figure 8. The control algorithm updates in real time to adjust to environment changes as they are encountered while directing Kezia to GPS waypoints. Using fuzzy logic allows Kezia to be tuned using a larger variety of variables and results in speed adjustments depending on the density of obstacles and lines per unit area. In wide open space Kezia will drive faster, but in tight spaces she drives slower to ensure enough time to react to obstacles yet undetected.

The specific membership functions and rule base used in the fuzzy logic are given here.

Additionally an example of the rule base used is given below in Table 2.
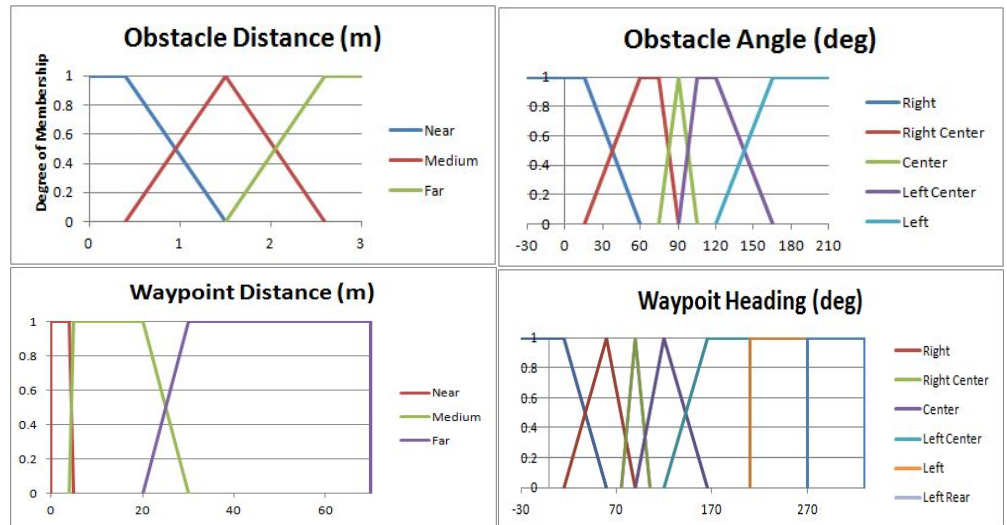

Figure 14. Input Membership Functions

Table 2. Obstacle Avoidance					
		Obstacle Angle			
		Right	RC	LC	Left
Obstacle Distance	Near	Slow/ No Turn	Slow/ Spin Left	Slow/ Spin Right	Slow/ No Turn
	Medium	Medium/ No Turn	Medium/ Big Left	Medium / Big Right	Medium/ No Turn
	Far	High/No Turn	High / Small Left	High/ Small Right	High/No Turn

Failure Analysis and Resolutions
Vehicle failure modes
Kezia failed to make sharp enough turns to avoid obstacles during rigorous tests, Kezia drove over lines repeatedly during initial tests. She lost the GPS waypoint list and suddenly wanted to go to a point 9,310 km due roughly east.

Vehicle failure points (electronic, electrical, mechanical, structural, etc) and resolutions
Programmed to have slow reaction/soft turns by mistake, running base speed too fast resulting in not enough processing iterations to react to obstacles, image algorithm filtering out lane lines in whole or part, Kezia had a mismatch of distance units and lacked code to implement a graceful program exit upon arrival at the final waypoint resulting in her thinking she had arrived at all waypoints sporadically and then deciding to do nothing or drive to a point farther out than the radius of the earth.

Failure Prevention

Tuned the fuzzy logic rule base to make Kezia react more sharply to obstacles and adjust weights of obstacles and target waypoint, tuned base running speed to ensure obstacles do not appear faster than they can be processed, tuned image thresholding and particle filter to obtain a sharp contrast between lane lines and grass and reject noise. We eliminated unit mismatches and implemented code to gracefully exit autonomous control upon arrival at a final waypoint .

Testing Overview

Simulation - Labview's integrated Fuzzy Logic Simulator allowed us to monitor Kezia's response to certain waypoint and obstacle position combinations without having to run Kezia through a course.

Lab testing - We set up testing in lab to obtain data to calculate the pixel mapping formulas we used to convert pixel locations to to real world 2-D spatial coordinates and ensure the accuracy of those the spatial coordinates to measured points in lab.

Real world - We ran multiple rigorous test runs of Kezia on mock IGVC courses with actual painted lane lines and obstacles. These tests allowed us to find bugs in the control algorithm and image processing algorithm. We were able to repeatedly adjust parameters and re-test until we eliminated the bugs.

Vehicle Safety and Reliability Concepts

E-Stop System

Kezia'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 wireless e-stop is a small, black remote with a single gray button. The remote has been successfully tested to a range of 50 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 Kezia's sensor mast while keeping the relay unit hidden in the electronics compartment.

Pedestrian Safety

Kezia's safety 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 Kezia'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 and a software program running as a separate thread in the main program.

Sharp edges on Kezia's frame have been rounded off, 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.

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

Computer Safety

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.

Performance Testing

Speed

Assuming the motor controller is linear from a minimum input of 0 to a maximum input of 127, the max allowed speed of 5mph grants speed control increments of .0394 mph. (For example, an input to the motor controller of 93 results in a motor speed of 3.66 mph.) We tested Kezia over a distance of 44 feet. To maintain a minimum average speed of 1 mph and a maximum of 5mph, Kezia must travel 44 feet in under 30 seconds but not less than 7.3 seconds. Kezia clocked in at roughly 21.5 seconds over a straight line distance at the current speed configuration resulting in a suitable speed of 1.39 mph.

Ramp Climbing Ability

From the body diagram of Kezia climbing a ramp it is seen the power needed to maintain a velocity is $P=\omega T$. Calculations from a simple free body diagram show then that **P= 48.7 watts** of extra power is needed above that needed for flat travel. One advantage of Kezia's control system is that the motor speed is controlled directly without reference to the output power. The result is stable speed regardless of incline or decline or flat.

Reaction Times

Compass refresh is 25ms. LiDAR scan time is 25ms. GPS refresh rate is 500ms. But most importantly the overall refresh time of Kezia is typically around 507ms. This number is vastly important because the higher it is, the slower Kezia must drive in order to be able to detect and react to obstacles in time.

Battery Life

Kezia's battery life was field tested to be longer than one hour under normal operating conditions. With the generator charging the battery and computer the expected battery life is around eight hours.

Obstacle Detection Distance

The Hokuyo LIDAR object detection range is 30m and the range of the Microsoft webcam is roughly 2.6m. While these numbers are greatly different, in theory and practice the great difference is suitable and justified. The Fuzzy Logic control algorithm has the distance "far" defined as greater than 20m. This is key because we anticipate Kezia largest turns to be the result of very wide obstacles and we would like to be able to react while still farther away. Furthermore, in practice, reactions to lane lines tend to be less drastic and thus require less detection distance for successful implementation.

Complex Navigation Situations

Kezia dynamically processes a single obstacle point at a time. Testing has confirmed this immensely simple, real-time method to be very effective at obstacle avoidance. Every control cycle Kezia reacts to a changing environment based on the closest obstacle point and the GPS target waypoint thus breaking down complex navigation situations into a set of simple maneuvers one after the other.

Waypoint Navigation Accuracy

We have found the accuracy of our arrival at a waypoint to be greatly varied. Sometimes we have driven to the exact spot of our waypoint, but other times we have been as far as three meters off. The difference depends on the conditions. If Kezia is in favorable conditions, it has SBAS (satellite-based augmentation system) methods enabled, and the GPS can provide better accuracy.

Performance Assessment

The robot is currently ready for assessment at the IGVC competition including the of capability of performing the following tasks:

- Lane following
- Obstacle avoidance
- Waypoint navigation
- Speed control

Cost Estimate

Table 3. Cost Summary

Subsystem	Cost	
Frame	$	849.02
Actuators	$	669.00
Electrical	$	1,761.37
Control System	$	1,150.00
Sensors	$	6,353.44
Suspension	$	593.27
Body	$	169.13
Total	**$**	**11,545.23**

Conclusion

Many improvements have been made to Kezia in order to compete in the 2016 IGVC. For example, we implemented an independent rear suspension design that enhances the mechanical abilities of the robot increasing the shock absorption. Additionally, we utilized a robot body that serves as protection from weather conditions and improves the aesthetics of Kezia. The LabVIEW control software capabilities were strengthened by developing a better image processing technique and implementing a fuzzy logic path planning algorithm. All of these improvements were combined to make Kezia ready for the competition.