University of Detroit Mercy Presents

SIRR Lancebot

IGVC 2017 Design Report

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Faculty Adivsors: Dr. Utayba Mohammed, Dr. Mark Paulik

Faculty Advisor Statement:

We certify that the engineering design in this vehicle undertaken by the student team, consisting of graduate students, is significant and qualifies for course credits in senior design and in the Master's program respectively

Advisor Signature: Mark J. Paulik

Introduction

SIRR Lancebot is a unique and innovative robot designed and created by the University of Detroit Mercy's Electrical Engineering senior class. SIRR Lancebot introduces a unique two wheeled balancing chassis configured with a 3D stereo camera fused with a 3D LIDAR sensor to provide 270 degree 3D scene analysis.

Design Process

Methodology - Our initial design process was based on the Quality Function Deployment (QFD) methodology in which we created a House of Quality graph organizing the requirements, priorities, and desired characteristics of our robot. The competition and its rules were considered as the customer and customer requirements respectively.

House of Quality - From the rules of the IGVC competition, Our team defined the success of our robot with four competitive advantages; A Swift, Intelligent, Responsive, and Resilient robot. These four attributes define our primary competition requirements, and the characteristics that we believe will give our robot a competitive advantage. Swift was chosen, as the time taken to complete the obstacle course counts as a significant factor in the scoring. Swift represents the agility and speed of the robot's movement, as well as the decision making capabilities. Intelligent was chosen to reflect the path planning algorithms and mapping. Resilient represents the capacity for the robot to rebound from unexpected events and withstand varying terrain and weather. Finally, responsive represents the robot's abilities to make accurate decisions in real time when given new data. From these attributes, further secondary and tertiary attributes were determined and correlated to engineering characteristics.

Team management - Based on the QFD results, the team was organized into five main groups, with two co-captains handling inter-group communication and discussion with the faculty advisors. While individual groups were given the freedom to operate on their own schedules, team wide meetings were held twice a week during which progress reports were given and team goals were set.

Table 1: Team Organization

Group	Members
Co-Captains	Mikael Paulik/Adam Fuchs
Hardware	Amadou Kane/Jason Hannawa
Lidar	Ryan Welsh/Jason Hannawa
Navigation	Rafael Orantes/Varkey Periyappurathu
IP	Philip Renn/Mikael Paulik
Wireless	Kaijun Wang/Adam Fuchs

Table 2: Costs

Description	Retail Cost	Team Cost	Comments
Chassis	$24,000	$24,000	Segway RMP 220 v3
Caster Wheel	$247	$247	Tractor Mode implementation
Aux Batteries (x2)	$729 each	$729 each	Peripheral device operation
Charger	$55	$55	For Batteries
Camera	$6,800	$6,800	Multisense S7
Lidar	$8,000	$8,000	Velodyne VLP-16
GPS	$22,070	Donated	Novatel Propak6
IMU	$1,425	Donated	Sparton
IMU	$15,000	Donated	KVH
NUC computer	$1,100	$1,100	Image Processing
Mini-box computer (x2)	$1,000 each	In lab	Mapping and Navigation
Router	$100	In lab	System integration
Aluminum frame	$400	$400	GPS and Lidar Mounts
Aluminum sheeting	$384	$384	Caster Wheel frame
Box	$100	$100	Battery housing
Camera Gimbal	$1,200	$1,200	Ronin DJI
Wireless E-stop	$24	$24	OrangeRx R615
Totals	$84,363	$43,768	xxx

Innovations

Balancing - The most prominent and readily visible aspect of SIRR Lancebot is the two wheeled chassis and the balancing algorithms used to drive the vehicle with superior mobility and speed. Use of this mode provides a very maneuverable robot with a minimal footprint. On rough terrain however, a wheeled balancing robot can produce somewhat unpredictable behavior, particularly when dealing with steep inclines. To make the robot flexible and permit use in a wide variety of environments we designed an easily removable caster wheel system was added to allow the robot the option of being run in a 3-wheel “Tractor mode”.

3d Lidar - Use of a 3D lidar allows both for more accurate readings of obstacles as well as the ability to distinguish certain aspects of obstacles (e.g. sawhorse obstacles). The sixteen channels provided by the lidar allow for multiple simultaneous hits when trying to verify the location of an obstacle as well as the differentiation between obstacles and inclines (such as ramps).

3D Camera - Use of the Multisense S7 allowed for color 3D stereo imaging which provides a means of easily extracting ground plane images which are devoid of obstacles. This makes it possible to accurately extract lane location data which can be fused with the Lidar point-cloud. The on-board stereo image processing greatly reduced processing time by allowing us process close to 20 3D frames per second.

Mechanical systems

Chassis and Drive train - The chassis was built off of a segway RMP 220 V3 robotic mobility platform provided by Stanley Innovations, and enhanced with aluminum frame structures to provide additional mounting points. The drive train that came with the system provides a peak torque of 100N-m per wheel. Without modifications, the chassis is capable of supporting 200lbs of payload, sports a top speed of 18mph, and is capable of driving up significant inclines in tractor mode. Multiple CAD renderings of the completed chassis are provided in Figure 1.

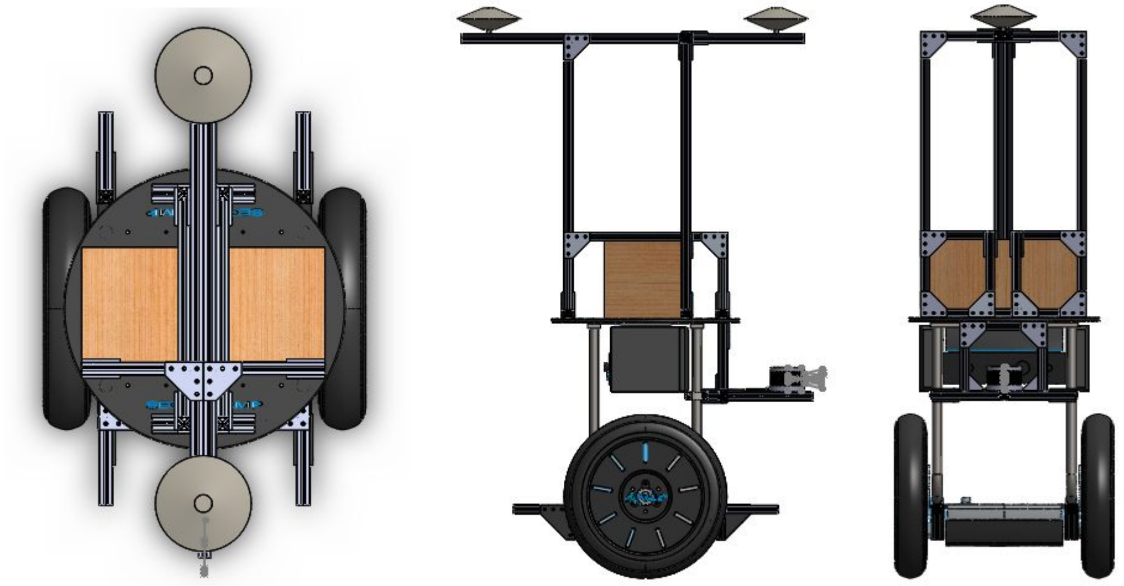

Figure 1: Top, Side, and Front views of SIRR Lancebot

Electrical/Electronics

Power distribution - With onboard computing and sensing components consuming a maximum power of 300W, we needed to consider a battery that would supply us with enough power to run for at minimum 3 hours, as well as easily replaceable and accessible. First we considered smaller electric bike “snap and go” batteries, although in order to implement the smaller batteries, we would have to wire them in parallel, and ensure that they simultaneously discharge at the same rate. If the two battery packs are not discharged in sync, one battery will attempt to charge the other, which could result in a fire, immediately eliminating this idea from consideration for our external power supply. Once we phased out the multiple batteries wired in parallel, we needed to consider one larger battery. We looked at the higher voltage supplies (for greater capacity), finally deciding on the Panasonic GA 18650 52V 24Ah Triangle battery pack. The 52V 24Ah pack has a maximum voltage of 58.8V and a cut off voltage of 39V, providing 1300Wh which enables our Segway robot to operate at max power consumption for 4.2 hours. If we opt to only use 80 percent capacity of the battery (roughly 1040 Wh), we can operate at max consumption for 3 hours. This should improve the number of charge cycles from approximately 400, to 1000.

The chargers considered for this 52V 24Ah battery pack, were all capable of handling an output voltage of 58.8V, which is 100 percent charge of our Panasonic battery, but the major constraint was time. We had to take into consideration that at a minimum, we can operate for 3 hours from one battery charge, so our second battery pack should always be fully charged and ready to be interchanged with our on board supply. Two of the three chargers in consideration have a maximum charging current of 5.0A, which would take 4.8 hours to charge our Triangle pack to

100 percent, and roughly 4 hours to an 80 percent charge. It would take more time to charge the battery than we would be consuming the power, this is not optimal. This instantly allowed us to disqualify these chargers from our consideration. Next we identified a programmable charger that has an output voltage of 24 - 60V and a charging current of 1 - 8A, which would allow our battery to be charged in 3 hours to 100 percent. This charger meets our time constraints in that we will always have a charged battery pack ready to be interchanged with our on board supply. Also with this charger, we can choose to charge to 80 percent battery capacity, which will inevitably increase our lifecycle count. If charging to 80 percent capacity, it will take 2.5 hours to charge, which is still less than the amount of time we can consume 80 percent of the battery power.

Power Budget

		Normal Operating Conditions			Worst Case Operating Conditions		
Device	Quantity	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)
Velodyne LiDAR	1	12	1	12	18	1.75	31.5
Carnegie Multisense S7	1	24	0.3	7.2	24	0.8	19.2
DVDO G3-Pro Air3C Pro	1	3	1	3	5	1	5
Netgear NightHawk X6 Wireless Router	1	12	0.55	6.6	12	1	12
DJI Ronin	1	Independent Power Supply			Independent Power Supply		
Microstrain 3DM-GX2 IMU	1	9	0.09	0.81	1	0.09	0.09
Spartan AHRS-8 Digital Compass	1	5	0.064	0.32	5	0.064	0.32
Intel NUC6i7	1	19	2.5	47.5	19	3.75	71.25
Mini-Box Computer	2	12	2.5	60	12	3.75	90
Novatel Propak LB Plus GPS	1	12	0.31	3.72	12	0.4	4.8
Warning Light	1	10	0.186	1.86	12	0.11	1.32
Wireless E-Stop/Arduino	1	12	0.045	0.54	12	0.465	5.58
TOTAL			8.545	143.55		13.179	241.06

Figure 2: Power Budget Worst Case

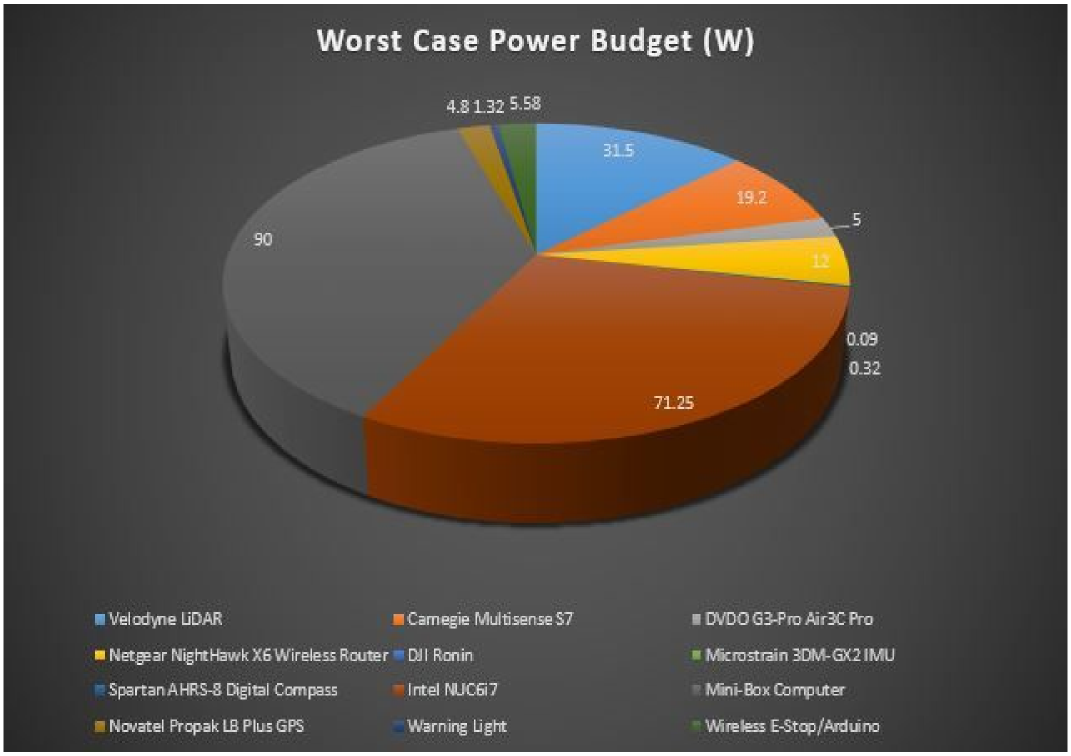

Figure 3: Power budget component comparison

Communication - In order to integrate the different processes spread over the three computers and robot's onboard computer, communication to the Robot Operating System (ROS) master was provided via the use of a centralized router. Both the camera and the lidar communicate via the ethernet protocol while the IMU units utilize USB. With these sensory devices connected to the computers, each computer was connected to the router, along with the chassis' onboard computer (for drive commands and balancing algorithm feedback).

Sensor Systems

Camera - The Multisense S7 stereo camera used for lane detection uses onboard processing of stereo algorithms to deliver real-time 3D point clouds of the environment. The camera provides a 80° horizontal field of view along with a 45° vertical field of view. Communication is done via Gigabit Ethernet protocol and is run using ROS drivers and an API.

Figure 4: Multisense S7 Stereo camera

Lidar - The 360° VLP-16 Velodyne lidar was used for physical obstacle detection. The unit offers an accuracy 3cm up to a range of 100m. In addition to a 360° horizontal field of view read at 0.1° intervals, the unit also provides 16 separate readings providing a 30° vertical field of view at 2° intervals.

Figure 5: Velodyne VLP-16 lidar

GPS - To obtain position data for the robot, the Novatel Propak6 dual antenna system was selected. Twin antennas are mounted on the vehicle's mast spaced 1 meter apart to allow for an accurate heading as well as a position reading within 4cm.

Figure 6: Novatel Propak6 GPS

IMU - SIRR Lancebot incorportates two IMU units for use with localization.The KVH CG-5100 is used to handle angular velocity and acceleration measurements for the vehicle. Additionally, the AHRS-8 Sparton unit is used for calculating the tilt and magnetic heading of the vehicle. These IMU units used in conjunction allow for SLAM based localization even if the GPS system were to go offline.

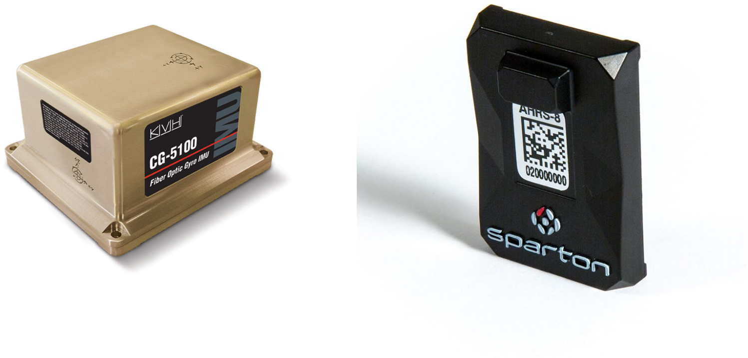

Figure 7: the KHV CG-5100 and AHRS-8 Sparton IMU units

Remote Control and E-stop system

In accordance with IGVC regulations, both a physical and a wireless e-stop were implemented on the vehicle. In order to accomplish this, we decided to use a wireless controller and modify it with an emergency stop button. The most important thing was that the controller had to work separately from our robot network, so that if the network were to fail, our robot could still be safely disabled. For this reason, we chose a 6 channel 2.4GHz transmitter and receiver module.

This transmitter and receiver pair transmits information in the form of pulse width modulated signals. The receiver has each of 6 channels then combined into one Pulse Position Modulated (PPM) signal, which is then read by the E-STOP module.

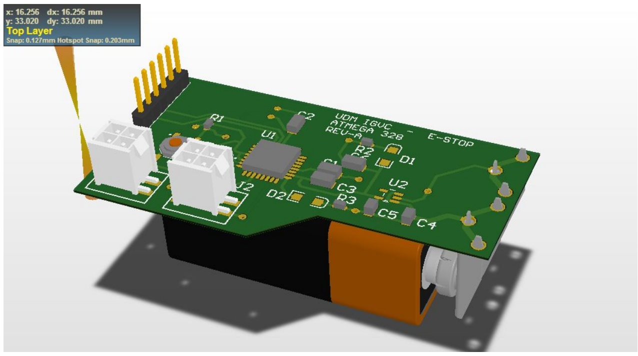

Figure 8: E-stop circuit board

Development Environment, Algorithms

Software development environment - As with previous years, the ROS (Robotic Operating System) is used as the primary development environment. Using a Java-based interface package, MATLAB is set to communicate with the ROS master. Matlab is used for execution of image processing algorithms for the associated ease of development and availability of sophisticated and efficient core image processing code blocks. ROS is an open source robotics platform that operates on a peer-to-peer model. In ROS all nodes can communicate directly with each other with minimal invocation of a centralized server. As the scale of the system increases to support more nodes, the load on the server remains manageable.

ROS has three layers of functionality. At the lowest level ROS operates on the basis of a network of nodes. These are modular processes that execute a specific task (such as read in and convert GPS data, transform coordinate frames, send velocity commands, etc.). Nodes communicate with each other by sending messages, using topics with specific names. Nodes can either publish messages to a specific topic or subscribe to one or more topics. The processing of these messages is used to direct the algorithmic flow, as needed. The ROS environment is effective not only for final implementation but also for simulation as it allows for the use of Gazebo simulations. Throughout the progression of algorithm development, Stage and Gazebo accommodate testing via simulation. The ROS/Gazebo simulators provide a representative and comprehensive simulation environment, complete with models for the robot, obstacles, GPS, camera, LIDAR, etc. Gazebo also provides a graphical depiction of robot motion within their environments Which offers a powerful tool to gauge the effectiveness of algorithms.

Enhancing frame rate - Central to the robot's ability to navigate an unknown obstacle course is the speed at which it can read in and process new information. Too slow of a frame rate results in a robot that cannot react quickly to new information. Maintaining a reasonable frame rate places a restraint on the level of analysis that can be performed on the information.

To achieve better frame rates, several factors had to be considered. The first is the camera configuration. Since the Multisense S7 allows for control of the desired frame rate as well as the published resolution it is possible to freeze the system by overloading it with data transfer. To prevent this, the frame rate was capped at 15fps (the frame rate of our algorithm) along with a reduced point cloud resolution (1024x544) to reduce the processing power needed to handle the data. Secondly, use of the 3D point cloud allowed for an immediate reduction of points processed by eliminating those that fell outside of the calculated ground plane. Finally, the 3D point cloud was processed using the OpenCV library (using C++) to provide greater efficiency compared to the Matlab environment. This allowed for the Matlab environment to only process a 2D ground plane image, greatly reducing processing time while still allowing for the ease of Matlab configuration parameters.

Mapping - In order to construct a static map of the IGVC course, lidar and camera results are fed into the Slam G-Mapping ROS package.

Path planning - SIRR Lancebot utilizes two path planning methods based on the constructed map. The Base_Global_Planner ROS package utilizes heuristics. For local path planning, the Trajectory_Rollout ROS package is used to account for vehicle speed and turn radius when generating a path that tries to match the generated global path.

Software

Image Processing - The image processing algorithm begins with taking the 3D point cloud and removing any points that do not fall on the ground plane. This allows for more efficient processing of the image as it removes any 3D obstacles that could cause confusion in the lane detection as well as allowing the algorithm to operate on fewer points, improving the speed. The remaining points' coordinate frame is then transformed so as to be relative to the base of the vehicle and then converted to a 2D metric image. This metric image is then processed using HSV thresholds to locate white lane lines, before using morphological operations to connect lane lines together and remove spot noise. Finally, the filtered metric image is converted to a laserscan message and published before fusing it with the lidar data.

Navigation - The ROS navigation package was utilized to drive the robot along the determined paths provided by the path planning algorithms.

Goal Selection - The Frontier-based algorithm ROS package moves the robot around an unknown environment while building a map to be used by the navigation algorithm. The basic idea is that the robot always goes to a frontier, which is a region on the border between known open space and unexplored space. The frontier's characteristics help the robot to avoid obstacles and keep it in a forward path once the lane lines are mapped as obstacles. In case the selected frontier becomes unreachable, the robot is sent to any other available frontier. The objective of using this approach is to minimize the possibility of the robot turning around and going in the opposite direction and also to escape some “fork” trap situations.

System integration - This project was divided into subtasks to facilitate development and assignment of tasks to individuals. However, this then requires a systematic process to integrate all the parts into a single, working product. The foundation of this was the design methodology discussed in the Design Process section. Using the ROS platform, each group was responsible for developing their own nodes for utilizing the data published by the vehicle sensors, or other processing algorithms.

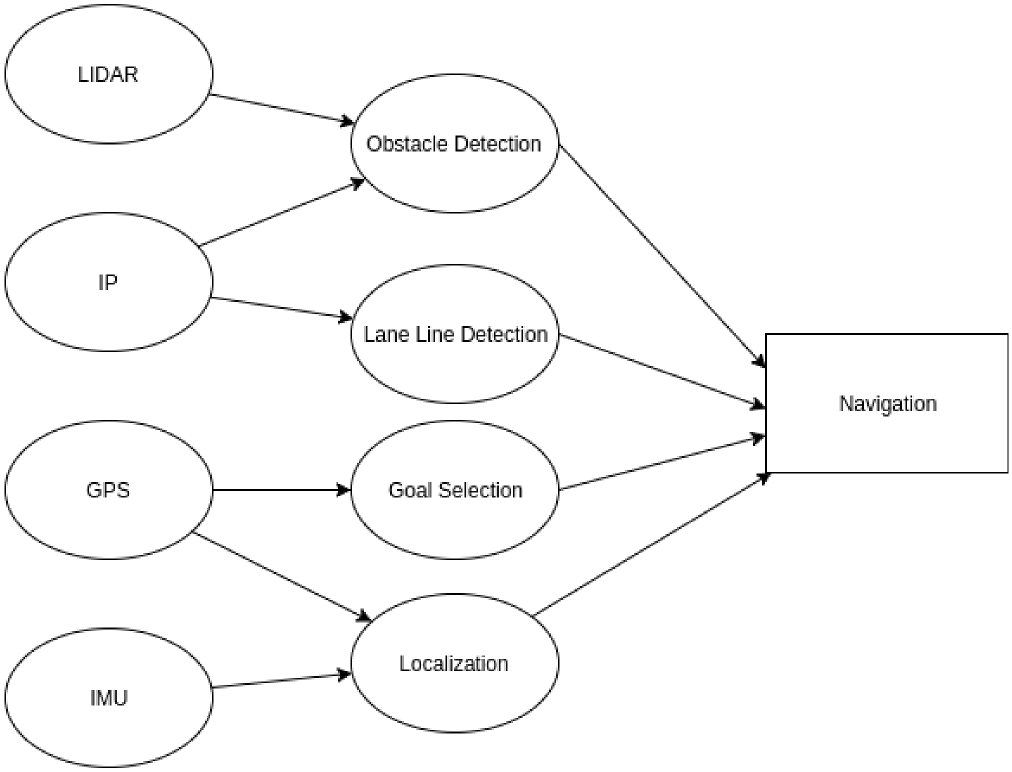

Figure 9: Sensor/Software Integration Flow Chart

Predicted Performance

Speed - Given the vehicle’s maximum operating speed of 18 mph, the frame rate can become the limiting factor. Operating at 15 fps, we obtain 15cm travel per frame while operating at the maximum allowed speed of 5 mph. This is judged to be reasonable given that local and global maps are being generated and utilized for navigation.

Ramp climbing ability - Operating SIRR Lancebot in balancing mode results in a recommended maximum slope of 5° while operation in tractor mode gives a recommended maximum slope of 10°. The Segway robot platform has been demonstrated to operate in much more aggressive environments (consider for example the nature of terrain that the Segway personal mobility platform can easily navigate). The performance limits are set with bystander and robot safety in mind. The use of a physical and wireless e-stop system mitigates concern over the use of the platform in more challenging environments. To enhance outdoor operation, we have installed deeper tread tires which provide greater traction. An optional set of cross-country tires is also available for the Segway platform but these have not been used due to the controlled nature of the IGVC environment.

Reaction time - Given the current image processing frame rate of 15 fps, we expect the robot to be capable of reacting to new information within 0.2 seconds

Battery life - Based on the power budget developed, a worst case scenario predicts a minimum of 3 hours of continuous operation. While the vehicle's 3 battery system provides a maximum operating time of 8 hours for the wheel motors and drive system, the peripheral systems for onboard processing powered by the additional Panasonic GA battery are the limiting factor

Waypoint/Navigation Accuracy - Given the Novatel GPS's accuracy of ∓4cm and the dual IMU system for kalman filter based sensor integration, the vehicle is expected to meet the 1 meter radius tolerance for the GPS waypoints.

Obstacle detection distance - While the lidar allows for obstacle detection up to 100 meters, this range would easily pick up obstacles outside of the actual course and serve no purpose. As such, the lidar data is only considered relevant for obstacles within 30 meters. Additionally, the camera FOV and orientation gives a lane detection range of up to 5.5 meters.

Safety, Reliability, Durability - Both physical and wireless e-stops have been tested to immediately halt the robot. Safety casters have been added to the front and back of the robot when operating in balance mode to prevent the robot from completely tipping over and damaging sensitive equipment. Should the robot tip to the point where it rests on these caster legs, the robot will cease operation (based on a 30 degree tilt sensor) to prevent further chance of harm.

Conclusion

The University of Detroit Mercy proudly presents SIRR Lancebot for the 2017 IGVC competition and is eager to participate.

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