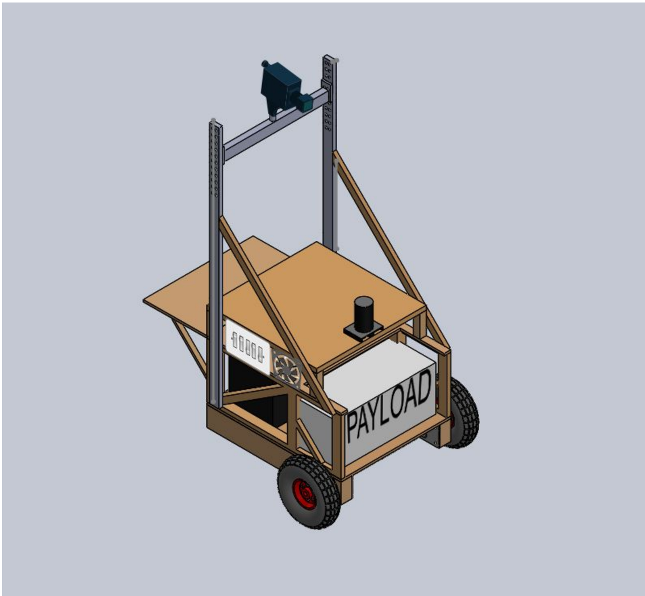
Indian Institute of Technology Kharagpur

Eklavya 7.0

15th May, 2019



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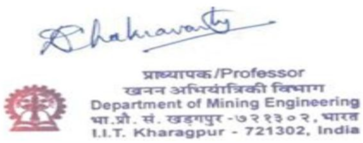
Faculty Advisor statement of integrity

I hereby certify that the design and development of the vehicle Eklavya 7.0, described in this report is significant and equivalent to what might be awarded credit in a senior design course. This is prepared by the student team under my guidance.



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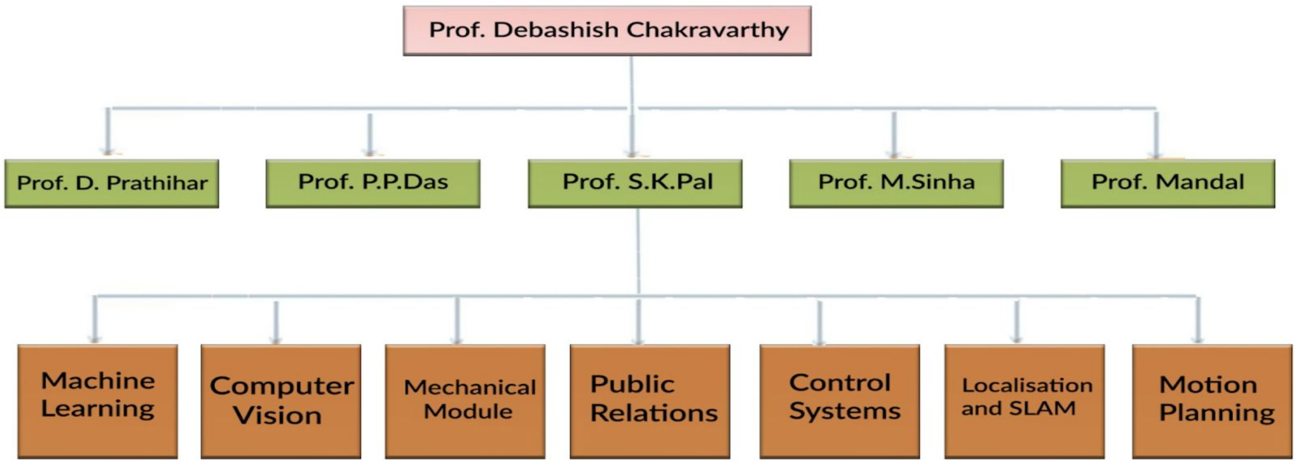
1. About us

1.1 Introduction

Team Autonomous Ground Vehicle (AGV), under the ambit of Center for Excellence in Robotics, IIT Kharagpur, has been pioneering autonomous ground vehicle technology with the ultimate aim of developing India's first self-driving car. The team has been participating in IGVC since 2011 with the Eklavya series of vehicles. Eklavya 7.0, another feather in the cap of the research group is all set to participate in the 27th Intelligent Ground Vehicle Competition (IGVC), Oakland University. With new robotic innovations, this successor of Eklavya series is much more efficient in all aspects i.e. mechanical, electrical and software.

1.2 Team organization

The effort behind this project was put in by a group of over fifty enthusiastic and intellectual undergraduate students from various disciplines of engineering of IIT Kharagpur.

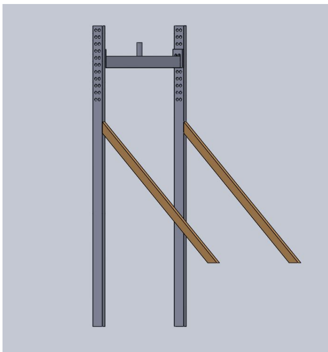


Team Organization

2. Innovations and upgrades

2.1 Innovative concepts from other vehicles

Innovating upon last year's fixed camera mount, this year we took inspiration from ClearPath Robotics' Husky robot and made a more stable, height adjustable camera mount, which vastly increased the accuracy of the vision pipeline.



2.2 Innovative technology applied to this vehicle

1. Mechanical innovations -

We are using aluminium sheets for waterproofing, which has several advantages -

1. It is very lightweight, so it does not shift the centre of mass.
2. It acts as a heat sink for the processing unit kept on top of it.

We have made a new foldable cover for the electronic systems which serves multiple purposes -

1. It protects the electronics of the robot from exposure to natural elements.
2. It acts as a surface for keeping the processing unit and mounting some sensors.

Castor wheel suspension has been used.

2. Electronic innovations -

1. Unscented Kalman Filter-Based Battery SOC Estimation and Peak Power Prediction.
2. Reverse polarity protection has been incorporated using MOSFET.

3. Software innovations -

1. Obstacles have been detected from both vision and LiDAR sensors for higher reliability.
2. Raw GPS data has lower accuracy than we require, so we have fused it with odometry to get a better estimate for the GPS.
3. Shadows have been removed based on variance properties in YCrCb color space.
4. Potholes have been detected by exploiting the constraint that the ratio of the root of the area by perimeter is constant for circles.

3. Mechanical design

3.1 Overview

The mechanical design of the Eklavya 7.0 is designed keeping in mind the general difficulties faced by the previous year's vehicle. The entire team brainstormed on the issues faced and possible solutions to the same and came up with the current design, which nullifies majority of the shortcomings of our previous designs.

Eklavya 7.0 is a three-wheeled robot vehicle with a wooden frame and covered by aluminium sheets. It has a differential drive mechanism and has two driven wheels and one rear castor wheel. It has mounts for placing sensors including a 2D-Lidar, PointGrey Blackfly camera and a GPS-IMU combination. It has a payload housing for storing the payload during the run. It also includes provisions for weatherproofing the robot for rough weather.

Broadly, it is a culmination of three regions of design which are:

1. Mechanical stability and easy manoeuvrability.
2. Ideal sensor placement and protection.
3. Space management and robust performance.

3.2 Vehicle specifications

Vehicle dimension: 2ft X 3ft X 4.26ft

3.2.1 Vehicle weight

Chassis weight: 20 Kg
Wheels weight: 2 X 1.5 Kg = 3 Kg
Castor Wheel = 1.5 Kg
Battery = 3 X 2.5Kg = 7.5 Kg
Embedded Equipments wires and sensors = 5 Kg
Payload = 9 Kg

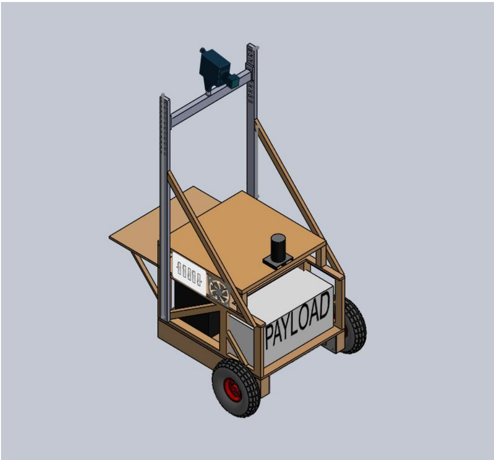
3.2.2 Motor Specifications

Rated Torque: 14.2 N-m at 175 RPM
Power = 100W
Rated voltage = 24V
Weight of Individual Motor = 1.45Kg
Rated Torque: 14.2 N-m at 175 RPM

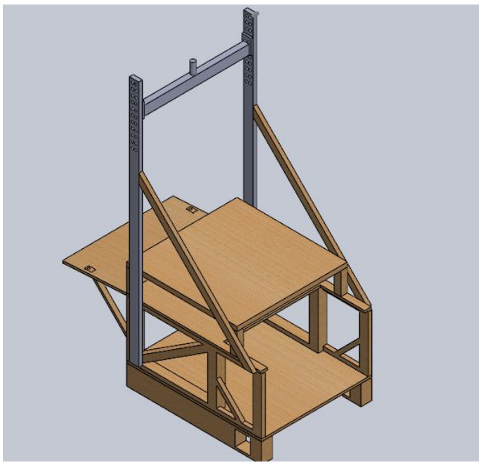
3.2.3 Center of Mass

X = 18.92 cm
Y = 66.99 cm
Z = 47.20 cm

3.3 Chassis design



Final CAD model



Space frame of chassis

The chassis design for Eklavya 7.0 is a modification over its predecessor Eklavya 6.0 with changes to address the various disadvantages faced by the latter in IGVC 2018. The chassis design can be analysed under the following objectives:

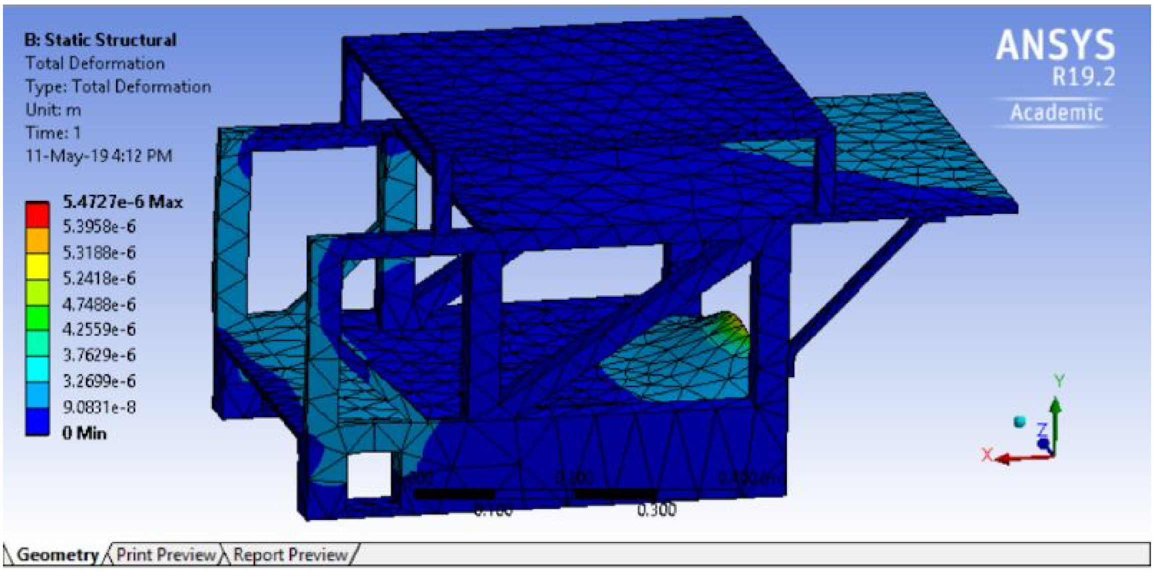
1 .Making the vehicle compact: In line with our stated aim of making the vehicle design compact and modular, the dimensions of the vehicle were significantly altered from last year's submission. A third of the chassis, which was redundant in its utility, was removed to optimise space utilisation and reduce weight. A lower and more central centre of mass of the vehicle (as opposed to forward skewed, due to loading of batteries and payload), ensured greater stability and robustness. The reduced wheelbase also resulted in greater manoeuvrability, improving on last year's movement.

2. Modularity: The bot frame has been improvised from a two storey design (the bottom one for batteries and payload and the top one for laptop and electronics) to a three storey design by introducing a middle compartment for electronic components, below an upper platform. This separate compartment ensures better performance because of higher cooling and efficient space allocation.

3. Efficient air flow behaviour for cooling of embedded systems: The chassis houses the embedded systems in an extended vertical housing with the front open that ensures a natural airflow intake during the run, and the heated air is allowed out of the housing through three fans. This method, from

observations, provided a much superior cooling to the embedded systems in comparison with the previous design.

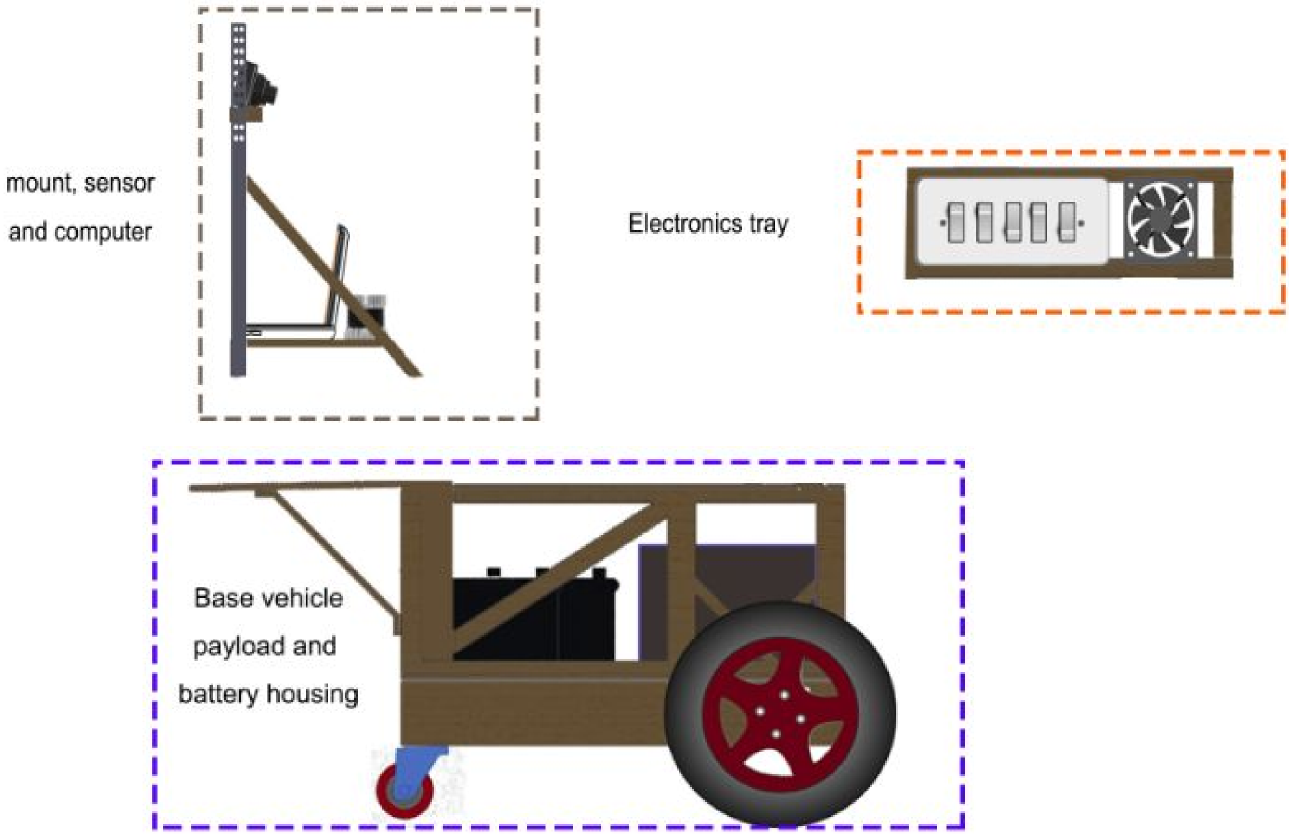
Static structural stability of the chassis:



The truss structure of the wooden frame showed considerable improvement to that of Eklavya 6.0 and had reduced stresses and strains in the static structural analysis of the chassis in a properly calculated force distribution.

3.4 Sensor frame and space distribution

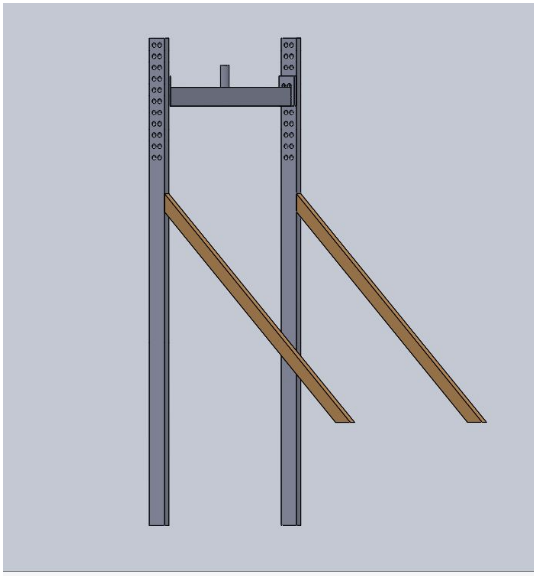
3.4.1 Sensor frame

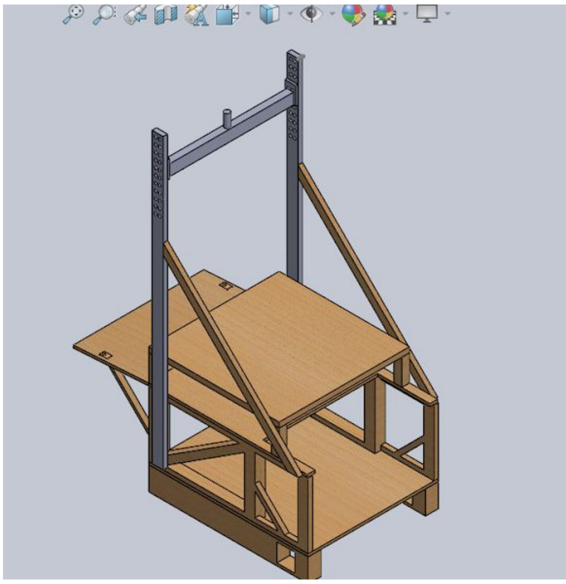


3.4.2 Space distribution

The compact nature of the vehicle brought challenges in space distribution due to the crunch of space available for all the accessories. The solution was to use a vertical expansion method by making spaces at greater heights, and the embedded systems were shifted upward hence making space available for all the different accessories. The lidar as well as the GPS-IMU combination are placed on the upper platform so that the “Transform Tree” can be easily generated between the different frames.

3.4.3 Modified camera mounts





The camera mounts in Eklavya 7.0 are modified from last year considering the problem of the great amount of vibrations and the difficulty faced in the assembly of the same. The single central rod from Eklavya 6.0 is replaced by a more robust rear wide base mount. The mount is a considerable improvement from that of its predecessor as it gains maximum stability from the rigid robot chassis and hence preventing buckling moments on the mount. The mount also adds modularity as it can be disassembled and assembled easily.

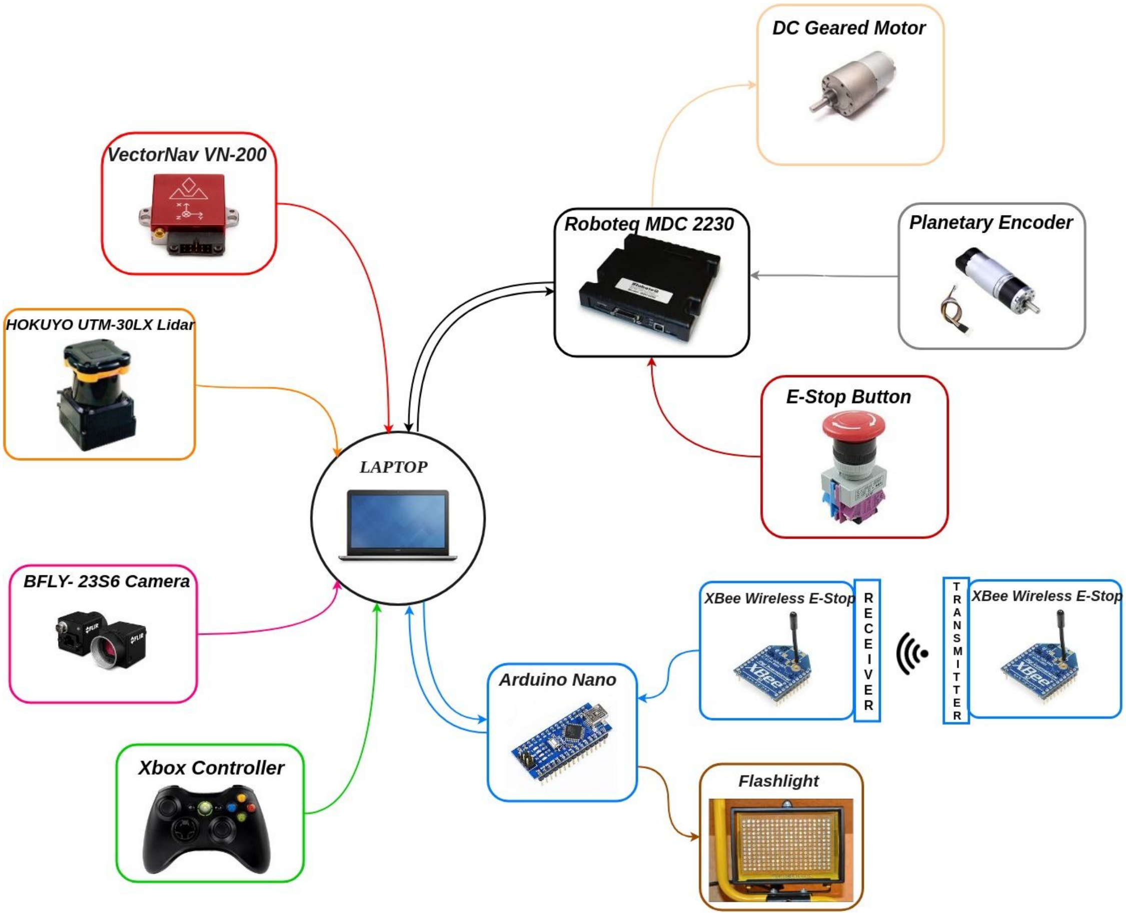
3.5 Weatherproofing

Eklavya 7.0 is designed to withstand light precipitation while providing protection to the sensors and embedded systems. The chassis is covered with lightweight aluminium plates that help in weatherproofing the vehicle without compromising the weight factor for the chassis. The plates cover the box encasing the embedded systems protecting them from any external disturbances. The sensor mounts are lightweight and also placed in protected casings to allow the undisturbed operation of the vehicle in lightly harsh weather conditions.

4. Embedded system architecture

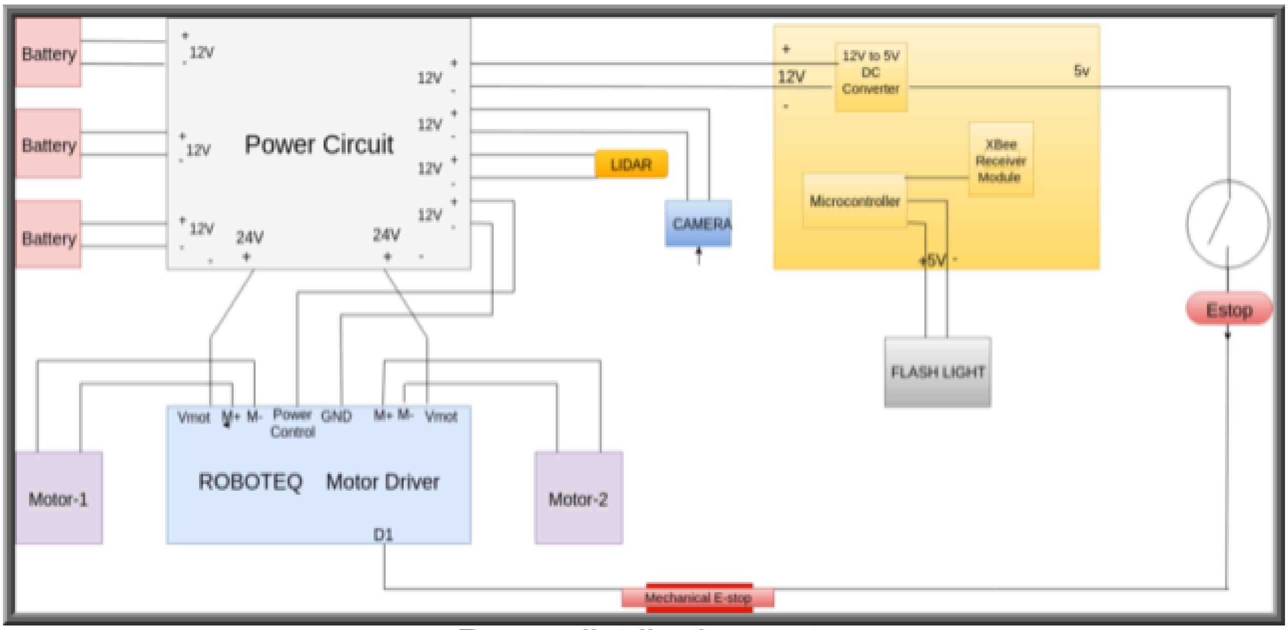
4.1 Overview

The Electrical system of Eklavya 7.0 consists of 2 high torque DC motors, Roboteq MDC2230 Motor Controller, sensors like Lidar, Camera, Encoders, GPS and IMU, Xbee for Wireless Estop and a Laptop. The design focuses on safety, robustness and dynamic controls. The complete electrical routing is shown below.



4.2 Power distribution

The self-designed circuit board provides all necessary operating voltages for each of Eklavya's components. Unregulated 12V power flows from the batteries to the power board, which is then converted to regulated 12V, 24V, 5V and 3.3V and sent to the respective sensors. The power board can run the overall system for about 1 hour 26 minutes on three 12Ah Pb-acid batteries. Each power connector for each of the components is protected by a fuse in case of a power failure.



Power distribution system

4.3 Power consumption

Table 1: *Electronics component power consumption*

Component	Quantity	Rated Power
Planetary Encoder Geared Motor	2	100 W X 2
Roboteq MDC2230 Motor Driver	1	10 W
VectorNav VN-200	1	0.5 W
HOKUYO UTM-30LX Lidar	1	8.4 W
BFLY- 23S6 Camera	1	2.5 W
GPS	1	0.5 W
Flashlight	1	4.8 W
Total		226.7 W

Hence the calculated run time of Eklavya 7.0's Motors with fully charged batteries is:

Minimum Time for other components = $\dfrac{1 \ * 1200 \ mAh * 12V}{26.7 \ J \ sec^{-1}}$ = 7.64 Hours

Minimum Time available for Motors = $\dfrac{2 \ * 12000 \ mAh * 12V}{200 \ J \ sec^{-1}}$ = 1.44 Hours

However, operating power consumption is less than half of the maximum power consumption. Hence, the vehicle can run up to 3 to 4 hours with all electrical components and sensors working together. Each battery takes approximately 1 hour to charge from a 12V 4A DC supply.

4.4 Electronics suite description

A laptop is used for processing the sensor data from the camera, LIDAR, IMU, GPS and encoders and a motor controller is used for driving two high power motors in a closed loop. Xbee is used for wireless emergency stop and the wireless controller is used for manual control. A 12V DC status LED panel is mounted in the vehicle to differentiate the manual and autonomous mode.

ELECTRICAL COMPONENTS SPECIFICATIONS	
Geared motor	Operating Voltage- 24V, Max current-30 A, No Load current- 1.12 A, Rated Torque- 142 Kg Cm, Gearbox Ratio: 1:6
Roboteq MDC2230 MotorDriver	Built-in high-power power drivers for two DC motors, Up to 60A output per channel , Dual Quadrature Encoder inputs with 32-bit counters. , Up to 6 Digital Inputs for use as Deadman Switch, LimitSwitch, Emergency stop or user inputs
VectorNav VN-200	3-axis accelerometer , 3-axis gyroscope , 3-axis magnetometer , barometric pressure sensor , GPS-aided Inertial Navigation System (INS) , Low power consumption , Accurate Signal output owing to Internal Kalman Filtering.
HOKUYO UTM-30LX Lidar	Range of 30 m in 270 degree Plane of device , Millimeter resolution in a 270° arc , Accuracy ±50 mm within a range of 0.1-30 m
BFLY- 23S6 Camera	On-camera image processing: color interpolation, gamma, and LUT , 16 MByte frame buffer; LED status indicator.
Planetary Encoder	2 Channel Quadrature Encoder , 2000 CPR

Table 2: Electrical components specification

4.5 Emergency stops

To ensure complete safety during the run, Eklavya 7.0 houses 3 independent modes of emergency stoppage.

4.5.1 Mechanical Stoppage Button

The Kill Switch is a red button located on the right side of Eklavya 7.0 at the height of about 2 ft from the ground. When switched on, the Mechanical Emergency stop is triggered and the motors brake.

4.5.2 Wireless Emergency Stoppage through Remote

A small wireless battery powered remote, containing a single pole single throw switch enables us to stop Eklavya 7.0 from distances up to 200 m. The remote uses XBEE S2C modules with Xbee/IEEE 802.15.4 communication protocol to communicate the stop signal to the Arduino Nano present on board, which thereby communicates the signal to the laptop.

4.5.3 Wireless Emergency Stoppage through Controller

The RB button on the wireless controller is also enabled to toggle the stopping of Eklavya 7.0, which adds to its control and safety while it is operating in manual mode.

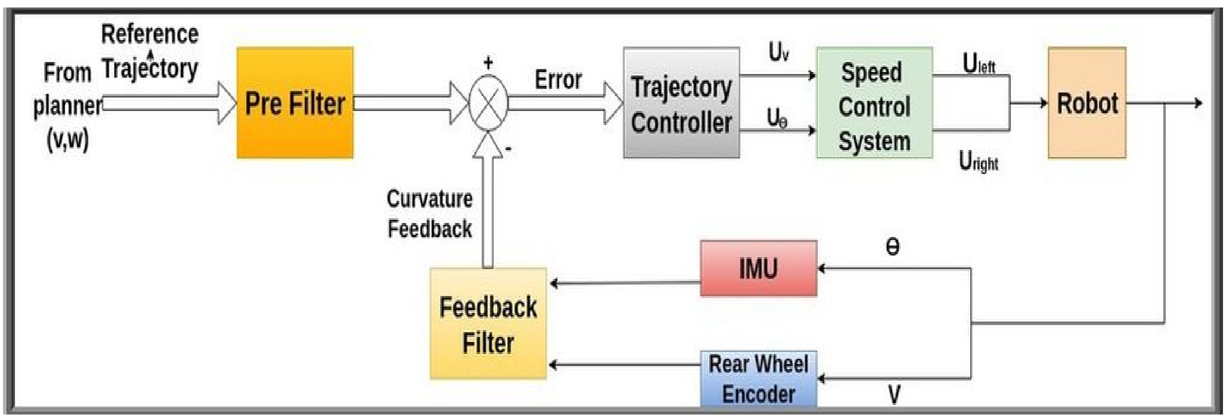
4.6 Control systems

The speed control system and the curvature control system are the main control systems of Eklavya 7.0. The control system is implemented on the Roboteq motor controller.

The speed control system tries to reject the environmental disturbances and tracks the given speed. The linear and angular velocities, as received by the planner are converted to differential velocities. PID control scheme is chosen because of its ease of implementation and the degree of freedom of tuning three parameters to achieve better performance. The speed feedback is obtained using the two front wheel encoders.

$$R = \frac{V_l + V_r}{2(V_r - V_l)} \; ; \omega = \frac{V_r - V_l}{l}$$

The experimentally tuned PID control scheme was verified by simulations on MATLAB. Using system identification techniques, a transfer function model was obtained for the two DC motors.
The Roborun utility of Roboteq helps in tuning the performance of the speed control system. The following block diagram explains the implemented control scheme.



Control system block diagram

4.7 Safety features

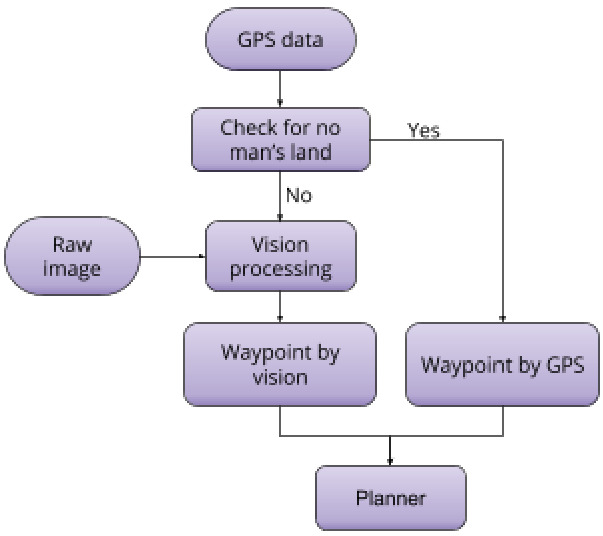
1. MCB and Fuses: Fuses and MCBs of proper current rating are connected to ensure no damage is done to the electrical components and sensors.
2. XT60 connectors are used at the battery terminals to ensure proper connection of the circuit with the DC power supply.
3. To provide proper ventilation to circuits, 3 exhaust fans have been installed in the structure.
4. LED indicators are used to detect any power cut/malfunctions in the battery.
5. Reverse polarity protection and current spike protection have been implemented.
6. Each sensor has its own switch and individual sensors can be switched off if needed. Heat shrinks are used to cover open wires.

4.8 Innovations and upgrades

1. Xbee S2C Module is used in Eklavya 7.0 instead of RF used in Eklavya 6.0, to ensure minimum interference and secure communication between the wireless remote and the vehicle. This results in secure communication of only useful data in minimum time.
2. We use a hall sensor to measure the current supplied to the motors by the batteries to ensure proper operating of the system.
3. To protect the system from reverse polarity an IRF9540 MOSFET is used directly at the supply. A mosfet is faster than a diode-fuse arrangement generally used for this purpose and further it provides a negligible potential drop.

5. Software architecture

5.1 Overview



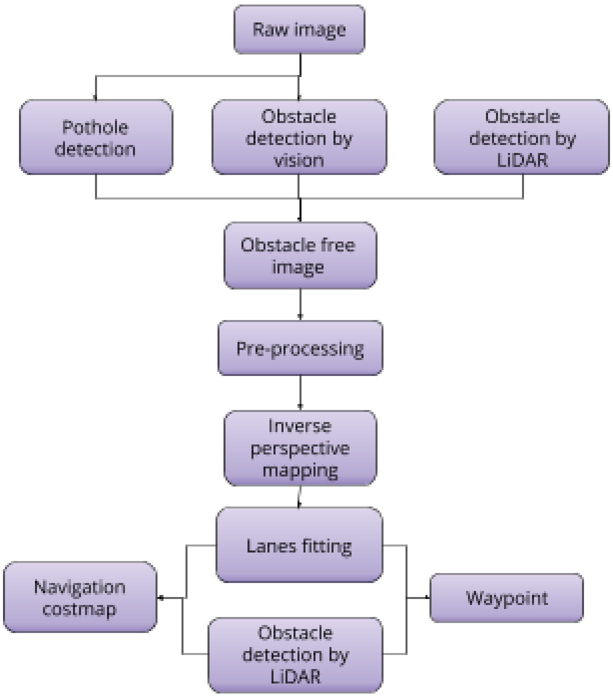
Overview of software system

We have designed the software stack of Eklavya 7.0 keeping robustness, reliability and computational efficiency at the core. Pipelines have been kept parallel so that failure of an individual module does not lead to failure of the complete system. Most of the codebase has been written in C++ to achieve low latency integration with the sensors.

5.2 Perception module

5.2.1 Overview

A monocular FLIR Blackfly camera has been used for vision. The lane detection was revamped this year, instead of only relying on traditional computer vision, to now fusing it with neural networks for better reliability.



Perception pipeline

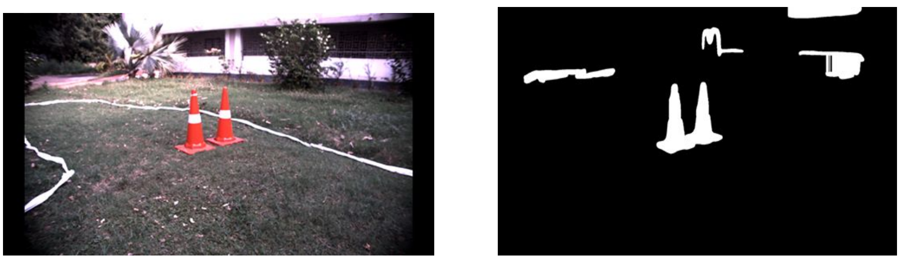
5.2.2. Obstacle And Pothole Detection

The pothole appears as a circle in the inverse - perspective image. We exploit the geometric constraint that the ratio of the perimeter and the square root of the area is constant for circles.

$$\frac{2\pi r}{\sqrt{\pi r^2}} = 2\sqrt{\pi}$$

Pothole detection

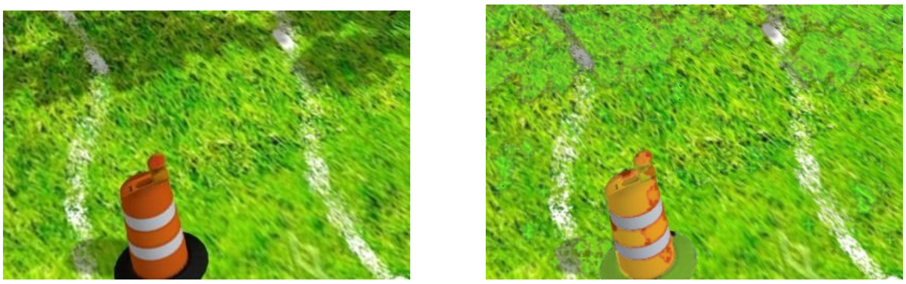
We use a linear combination of colour channels to detect obstacles which interfere in the proper detection of lanes.



Obstacle detection

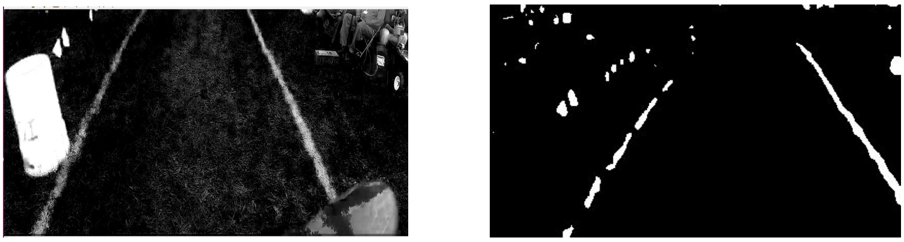
5.2.3 Lane detection

Shadows posed a major problem for the vision module. Shadow patches were easily confused with the lanes as both exhibited identical contrast characteristics. Shadow removal was done based on finding pixels with intensities between two standard deviations from the mean in the YCbCr color space.



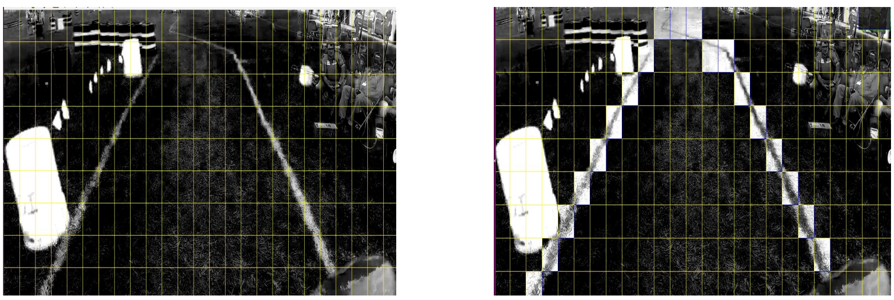
Shadow removal

This was followed by fusing combination of channels like ***2B-G***, ***B***, ***2B-R*** and ***BGR^2***.



Linear combination of colour channels

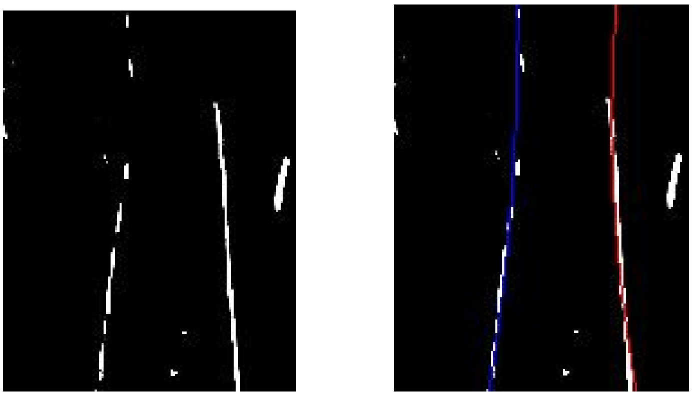
The image may still contain some maximal intensity patches due to sunlight. To remove these, a neural network was trained to classify each patch as lane or non-lane. A small network was used as it sufficed for the minimal features that patches have and also aided in faster and GPU independent inference.



Data Collection For Training Neural Net

5.2.4. Curve fitting

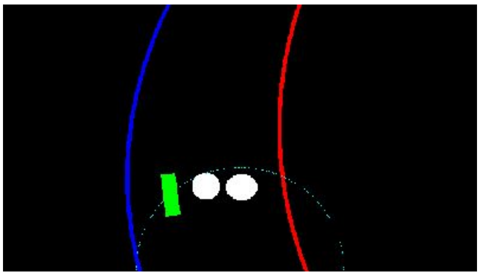
After removing shadows, a quadratic curve is fit on the binary image by using the RANSAC algorithm. RANdom Sampling And Consensus (RANSAC) is an iterative method for robust fitting of models amongst many data points. There are other more robust model fitting algorithms like MLESAC, but we stick with RANSAC after careful consideration of the trade-offs between computation time and robustness. For all practical needs, RANSAC uses minimal computational resources.



Curve fitting using RANSAC [Left lane - blue, right lane - red]

5.2.5. Waypoint generation

Lanes detected from the previous module are published on the cost map used by the planner for path generation. Using the cost map, which contains the lane and the obstacle information, we compute a suitable waypoint for local navigation that lies within the lane boundaries but not on an obstacle. A semi-circular arc is drawn 3 metres from the robot and such a point on the arc is chosen, which lies between the lanes and is farthest from the obstacles.



Waypoint generation [blue and red lanes, white obstacles, green robot]

5.3 Planning module

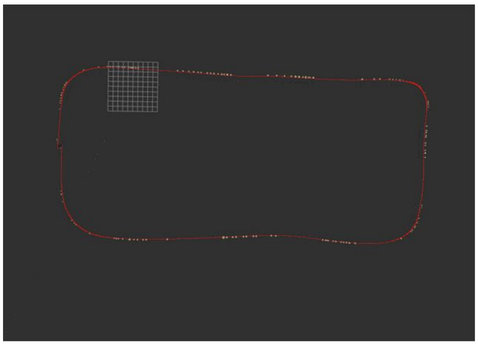
This module plans an optimal trajectory between the current bot's position and the destination waypoint generated through the perception module by using a local and a global planner.

Global Planner : The perception module provides the planner with waypoints to traverse through the field. These waypoints are sequentially provided to the planner, which then uses the A-Star algorithm to generate an optimal path from the current position to these way points taking care of the obstacles in between.

Local Planner : The local planner takes in the pathway points and produces a linear and angular velocity profile which takes care of the kinematics along the generated path. We use the Time Elastic Band Local Planner (TEB planner) for an efficient result.

5.4. Localization

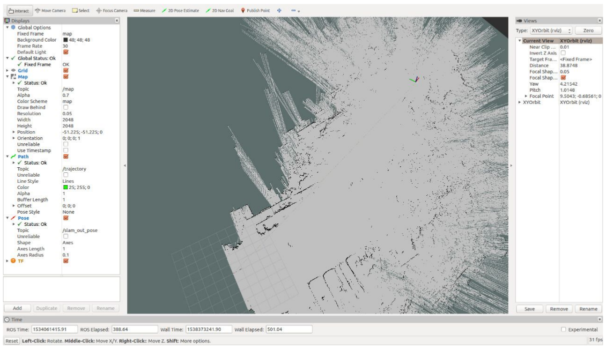
Localization is handled by fusing the data from different onboard sensors namely: GPS, IMU and feedback from wheel encoders using Unscented Kalman Filter (UKF), which is an improvement over the existing Extended Kalman Filter. UKF uses selected sigma points which are then transformed onto the sensor space and the predicted mean and covariance is recalculated, hence providing a better nonlinear state approximation. We run two ROS nodes to fuse state information in both map and Odom frames, to obtain an accurate estimate of the robot's state.



Odometry estimate around a loop

5.5. Mapping

To map the environment, we use the grid mapping algorithm with Rao-Blackwellized particle filters as a SLAM based solution. The LiDAR input is stitched at each time instant using the relative odometry information between the initial and the current state estimate. By combining and matching the scan points between time instances, the robot is able to localize itself in the map.



Mapping using SLAM GMapping

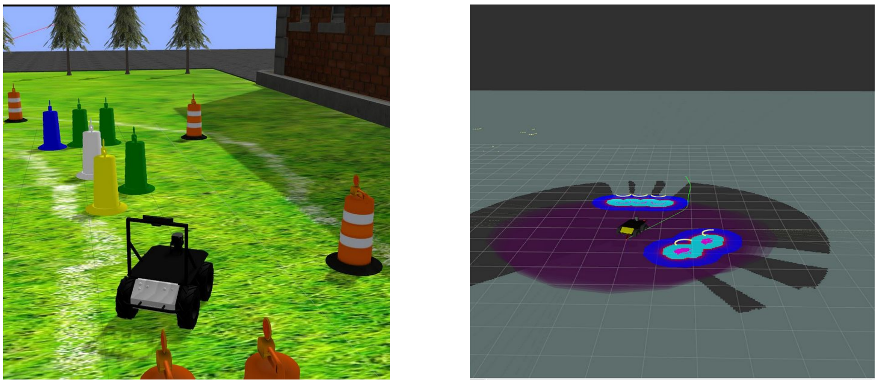
6. Failure modes

1. From the Ansys simulation of the chassis, structural weak points are found to exist at the castor joint. Under excessive stress, the castor joint may stop working. To overcome this, a spare castor wheel is carried.
2. If the vehicle is not giving an accurate value of the GPS position, check that the number of triangulating satellites is greater than 4. For better GPS data, move to an open ground.
3. If the motors are not working properly, check that oil is not leaking. Spare motors are available if motors are permanently damaged.
4. If all seems to work fine but the vehicle does not move forward, check if the mechanical stop is pressed.
5. Overheating may lead to high temperatures inside the machine. Check if all the 3 exhaust fans are working properly and none are blocked. Fans should be restarted to restore normal working temperature.

6. If lanes are not detected properly, check that the camera is set to the correct focus. The manual switch on the camera can be used to change the focal length.
7. Motor controller malfunction - mechanical or wireless E-stop switch stops the controller immediately. Spare motor controllers and sensors are available.

7. Simulation

To aid testing, we used an open-source simulation platform Gazebo to simulate and test our planning and perception modules. We created an OSRF world in which we built a track similar to that there is in the competition. The simulator is interfaced with the ROS environment. We used a URDF model of a differential driven Husky UGV , which is similar to our IGVC vehicle. We modelled the noise as a Gaussian and added it to the sensor output to make the simulations more realistic.



IGVC course simulation for testing

8. Cost Estimation

Component	Quantity	Retail Cost (USD)	Cost to Team (USD)
Roboteq MDC2230 Motor Driver	1	275.00	275.00
VectorNav VN-200	1	2600.00	0 (Sponsored)
BFLY-23S6 Camera	1	575.00	575.00
HOKUYO UTM-30LX Lidar	1	4974.00	4974.00
Planetary Encoder Geared Motor	2	210.00	210.00
Asus FX553VD	1	1000.00	1000.00
Xbox 360 Wireless Controller	1	35.00	35.00
Lead Acid Battery	3	92.40	92.40
Arduino Nano	1	3.74	3.74
Miscellaneous Circuit Elements	NA	70.00	70.00
Rubber Wheels	2	20	20
Building Materials and Fabrication	NA	150	150
TOTAL		10005.14	7405.14

Table 3 - Retail cost and cost to team