DELHI TECHNOLOGICAL UNIVERSITY

ZEPHYR

15th May 2018

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I hereby certify, as the faculty advisor, that the design and engineering of the vehicle outlines in this report to be entered in the 2018 Intelligent Ground Vehicle Competition has been significant and equivalent to what might be awarded credit in a senior design course.

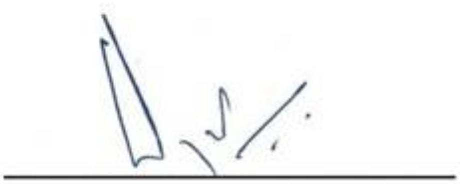

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Table of Contents

1. Team Identification, Team Organization and Design Process

1.1. Introduction

The Intelligent Ground Vehicle team from Delhi Technological University, India is proud to introduce Zephyr in IGVC 2018. It is the first the time the team is participating in this competition and with a great zeal to explore and learn the technology that powers intelligent vehicles; we have developed Zephyr–a smart, autonomous, differentially-steered vehicle which can maneuver within specified lanes while dodging obstacles and potholes to reach a goal guided by GPS waypoint navigation.

1.2. Team Organization

We believe that team work is at the heart of great achievement and as a rookie team our goal was not just to develop an autonomous vehicle but also to build an environment which nurtures team and indiviual's growth simultaneously. To ensure that the team functions as a well oiled machine we ascertained that there is good communication among members, effective knowledge transfer, every member shares common vision and everybody passionately takes initiatives and holds up on their responsibilities.

The team consists of seven undergraduate students from different engineering disciplines. The members were assigned roles on the basis of their knowledge, experience and interests. The members from mechanical department were incharge of designing the chassis, drive train, setup sensor mounts and organizing electrical housing. The electrical team was in charge of designing the circuit boards, distributing the power to the various on-board computers, and wiring the robot efficiently. The software department dealt with the identification of obstacles and lanes; this information was then used in a costmap to calculate a path from its current position to the GPS way point. The administrative procedure for the team is managed by one member and the responsibility of logistics and operations were assigned to members on ad hoc basis.

TEAM MEMBER	MAJOR	ROLE
Divye Bhutani	Software Engineering	Vision/ Path Planning
Pranshu Pant	Mechanical Engineering	Navigation/ FEA Analyst
Yusuf Ali	Mechanical Engineering	Design/ Fabrication
Tinandumoy Bose	Mechanical Engineering	Design/ Fabrication
Ishwar Mukesh	Automotive Engineering	Battery Management/ Control System
Kunaldeep Kalita	Electrical Engineering	Corporate/ Administration Dealing
Nilay Pant	Computer Engineering	Logistics/ Operations

1.3. Design Process

As first year participation the team sorts to external initial literature available on IGVC website and getting in touch with the teams who have participated in IGVC in past to critically analyze the problem statement and recognize associated risks involved at every stage of development. Once the problems have been examined the team held regular meetings in planning the further course of action. At this stage we explored the hardware components, software framework, integration interfaces available and ascertained our course of action. An estimation of the time and effort commitment required was drawn and was well communicated to each member of the team and with this we step into designing phase where we constructed a conceptual design which determines functionality of the system and a technical design which governed how the functionality will be achieved. Concurrent development by different departments of the team was initiated and every department undertook rigorous testing of their deliverable before integration into a complete system. After successful verification of unit testing all the modules were integrated using suitable interfaces and we conducted severe system testing. The results obtained from the system testing were validated against our problem statement and the faults were handled.

Figure 1 Design Process

2. Innovations

- **Collapsibility and Transportability:** Zephyr's mechanical design enables it to reduce its form factor to **60%** of that of the normal working state. This prominent aspect of the design facilitates the effortless and economical transportation of the bot to the competition, as Zephyr – in its collapsed state – readily fits into standard suitcases permitted over international flights.
- **Modularity:** Zephyr's structure has been primarily divided into three parts that enable easy troubleshooting and maintenance by enhancing accessibility to its various constituents. The three parts include: Main body, Processing unit enclosure, Electronics
- **Quick Assembly:** The collapsibility and transportability features of Zephyr also facilitate its expeditious assembly from scratch. Zephyr can be assembled into its typical working state in well under 30 minutes – minimizing the downtime during transportation and supplementing serviceability.
- **Highly Accessible Processing Unit:** The laptop – which is Zephyr's central processing unit – can be easily slid out of the independently attached processing unit enclosure to facilitate swift troubleshooting and ensure optimal downtimes between Zephyr's successive runs.
- **Adjustable Sensor Mounts:** Self-developed alterable sensor mounts were developed for the cameras and the LiDAR sensor which enabled quick adjustability of the sensor's relative orientation with respect to the bot during testing sessions.
- **Intelligent Current Distribution System at Charging Port**: Zephyr constitutes an intelligent current distribution system that redirects current from the charging station to the processing unit or the on-board battery by monitoring in real-time the remaining battery percentage in each of the aforementioned.

- **Temperature Controlled Cooling System :** An intelligent cooling system is featured in Zephyr which monitors real-time on-board temperatures and regulates the required of the cooling fans to ensure optimum cooling under all conditions.
- **Health Monitoring System :** Zephyr is equipped with a battery voltage monitoring system which displays the real-time battery percentage of the vehicle by indicative LED lights. In addition, Zephyr has a real-time heat-dissipation monitoring system which is regulated by a temperature sensor and an associated microcontroller. The afore-mentioned is used to regulate the real-time RPM of the cooling fan so that it utilises the battery in the most optimised manner without compromising on the cooling of the vehicle.
- **Use of Teflon Coated Wires:** Zephyr's entire wiring harness consists of industrial grade Teflon coated wires which are designed to endure temperatures of up to 250 degree Celsius - adding to the safety ruggedness of Zephyr's electrical connections.

3. Cost Estimate

ITEM	SPECIFICATION	COST
LiDAR	SICK LMS111	$4900
GPS	AtlasLink GNSS	$4565
IMU	Sparton AHRS-8P	$1840
Laptop	Dell Inspiron	$1160
Battery	Booant Battery	$530
Aluminium Raw Material	T-Slot Al-6061 Extrusion, Aluminium Sheets (6 series)	$295
Hub Motor	Hoverboard Motor	$240
Machining Cost	Laser Cut/ Welding/ Lathe Operations	$115
Cameras	Logitech B525	$80
Microcontrollers	Arduino	$70
Transmitter	Flysky	$55
Motor Driver	BLDC ESC	$45
Acrylic Sheets	4mm thickness	$40
Cooling Fan	Sunon	$25
Wires and Misc	Miscellaneous	$50
Sliding Channels	Hettich	$10
	TOTAL	**$14020.00**

The project was undertaken in November, 2017 and since then immense time and effort has been devoted to IGVC Project. On an average each team member has spent 30 hours per week, amounting to total 720 person-hours since the inception of the project.

4. Mechanical Design

4.1. Overview

Zephyr's mechanical design revolves around the three basic design considerations that enable it to produce the best of results considering various competition parameters as follows:

- Track layout
- Nature of road profile
- Maximum and minimum speed
- Nature of obstacles
- Ease of testing and serviceability

On a holistic analysis of the above-mentioned parameters, the team ascertained that the mechanical design of Zephyr would have the following characteristics and every design-related decision would be centered about them. They are as follows:

- Lightweight and rigid structure
- Efficiently packaged design
- Ease in maneuvering the robot
- Highly reduced assembly downtime

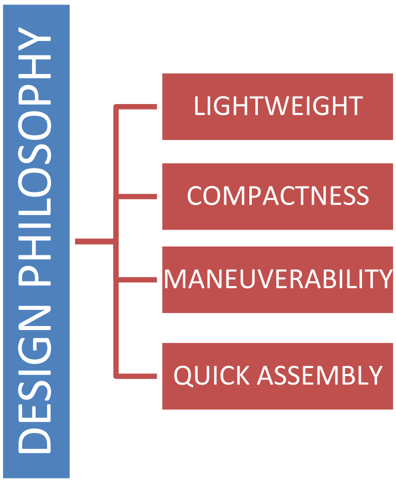

Figure 2 Design Philosophy

Since this is the team's first competition season, the mechanical department had ascertained that the design strategy would strongly adhere to the iterative process undertaken for the entire project. Multiple designs were developed using Dassault System's SolidWorks software keeping in mind the basic mechanical constraints stipulated by the IGVC rules. Each design built upon its predecessor and recursive optimizations ensured flawless and efficient output. A brief overview of the evolutionary design approach has been summarized below – depicting how each iteration led to the freezing of the current mechanical design.

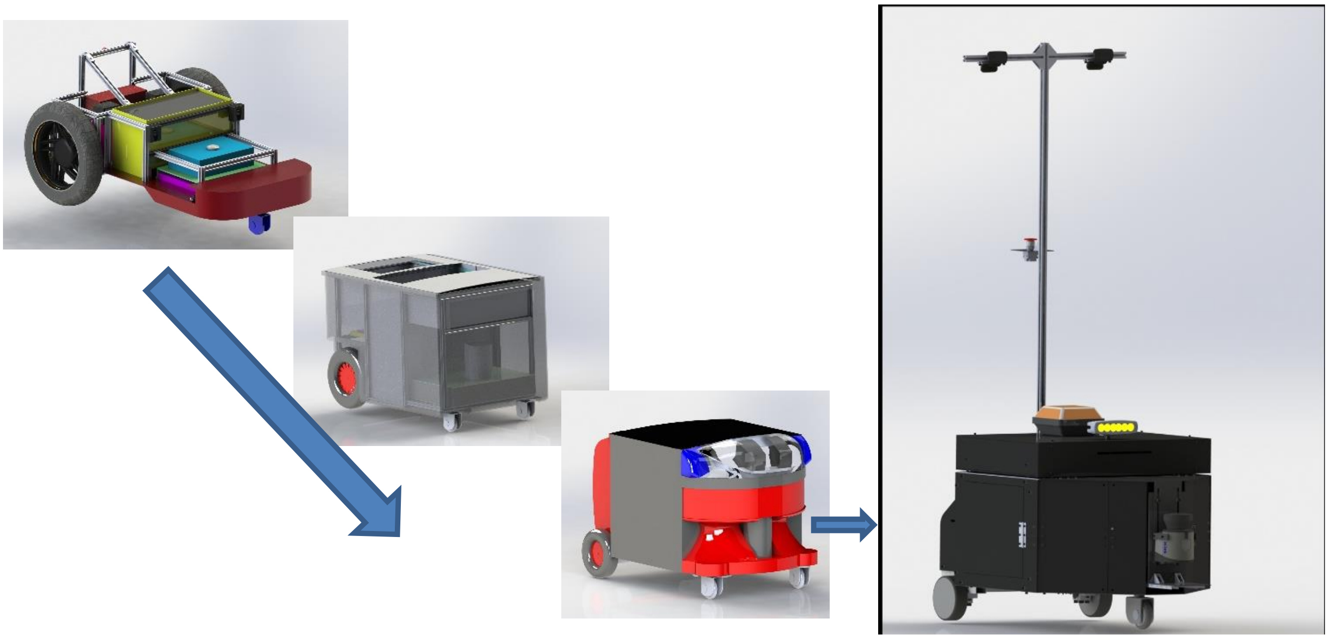

Figure 3 Evolutionary Design Process

4.2. Chassis and Body Design

Zephyr's dimensions adhere to the minimum geometric constraints stipulated by the competition which ensure high packaging efficiency and improved maneuverability of the robot. In addition, it has been critically focused upon to position Zephyr's center of gravity as close as possible to the ground to mitigate toppling tendency and increase overall stability of the robot. Moreover, Zephyr constitutes a highly symmetric weight distribution which again provides for increased balance and rigidity of the frame. This also helps in providing for a sharp turning radius – enabling Zephyr to revolve about the vertical axes passing through motors.

4.2.1. Material Selection

In order to fabricate a lightweight overall structure for Zephyr, 20 mm x 20 mm T-slot aluminum extrusions have been used in conjunction with 2mm thick aluminum sheets for further reinforcement. Extrusions were considered for erecting the primary structure as they have a high section modulus – enhancing their strength to that of steel. Moreover, aluminum extrusions are an industrial standard and are an economic and accessible option from the viewpoint of the market. Aluminum reinforcements were reduced to precise required dimensions facilitated by the laser-cutting process. All material considerations were done through thorough structural analysis using ANSYS 16.0. To ensure that Zephyr remains aesthetically appealing, acrylic sheets have been used for covering the entire primary structure. This helps to keep the entire frame weatherproof as the acrylic sheets prevent the seepage of water into the same. The afore-mentioned choice of materials enabled Zephyr to weigh in at under 50 kgs – which is considerably lighter than most other counterparts attending the competition.

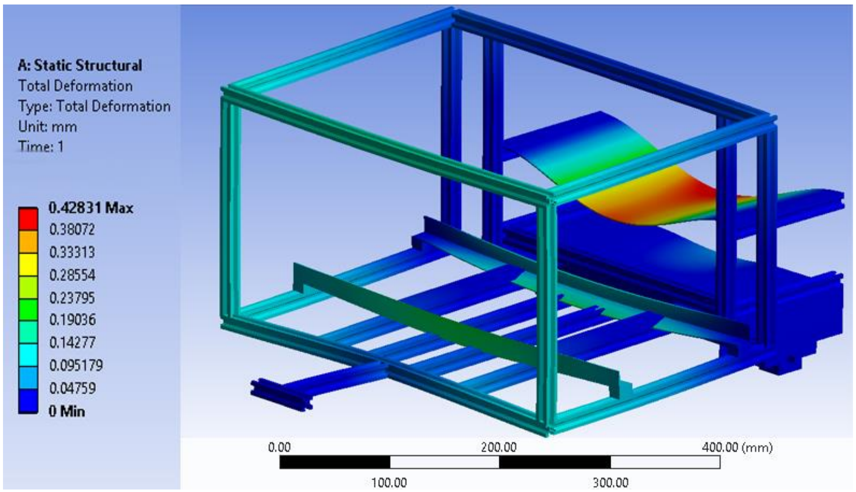

Figure 4 FE Analysis

4.2.2. Collapsible and Modular Design

At every stage of the design process, it was emphasized that the entire structure should be modular in nature. In addition, it must be easy to assemble and transport enabling highly reduced downtimes between testing and transporting sessions. Zephyr's body has been critically designed such that it can reduce its form factor by about 60% in non-working conditions which helps in easy

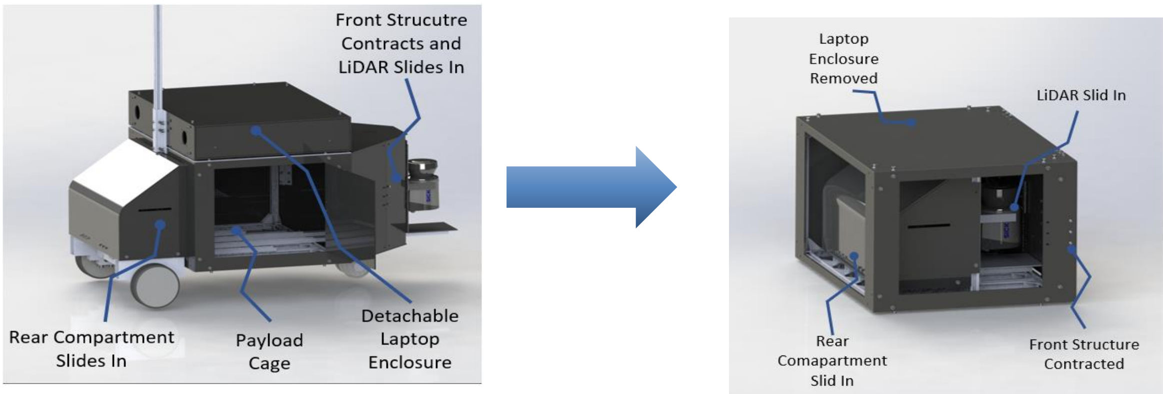

Figure 5 Collapsible Design

transportation of the frame.

4.2.3. Drivetrain

Zephyr incorporates two driving wheels in the rear part of the structure and a driven caster wheel at the front for balancing out its overall weight. The rear wheels are powered by two independent BLDC hub motors. As mentioned earlier, this eliminated the need of incorporating a gear box as the hoverboard's hub motors were optimally suited to drive our robot without any gear reductions. The motor mounts were manufactured in-house on a lathe machine.

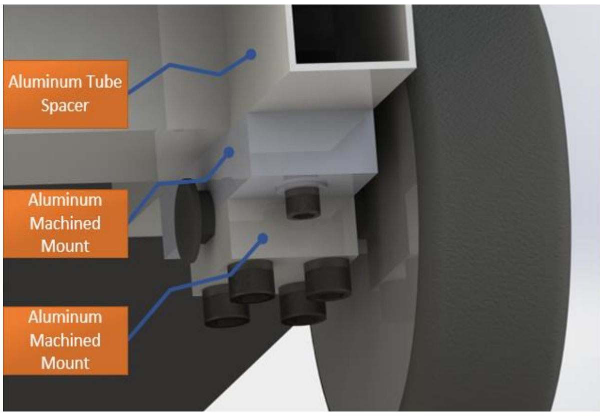

Figure 6 Drivetrain of vehicle

4.3. Frame Structure, Housing, Structure Design

4.3.1. Adjustable Sensor Mounts

The sensor mounts for the LiDAR cameras have been designed such that their orientation with respect to Zephyr's structure can be altered so as to produce the most optimum on-track results. The camera mast incorporates the adjustability in the orientation of the cameras. The LiDAR's mount allows for a total variability of 30 cm in its height from the ground.

4.3.2. Camera Mast

Zephyr's onboard cameras are mounted on a 20 mm x 20 mm T-slot aluminum extrusion which helps to provide flexibility and adjustability in the mounting of the cameras along the length of the extrusion and along the length of the camera mast. Moreover, the adjustability in the orientation of the cameras does not hamper the rigidity of the mast as it is securely attached to the primary structure using standard, rigid L-connectors.

4.3.3. Laptop Access Panel

Zephyr's central processing unit is a Dell Inspiron 15R laptop - housed in an independent casing which can be bolted onto the primary structure of Zephyr. The casing in itself allows for a sliding access to the laptop so that the processing unit is easily accessible at times of troubleshooting.

4.4. Suspension

Upon a critical analysis of the suspension systems of various vehicles that have performed exceedingly well in the competition. Rough, back-of-the-hand calculations tend to indicate that the benefits provided by the suspension system are clearly outweighed by the reduction in manoeuvrability of the vehicle due to increased inertial mass on the same.

4.5. Weather Proofing

Acrylic plates form Zephyr's outer body enabling it to function in rugged and extreme conditions. In order to ensure minimal seepage of water into the primary structure, the inner edges of the acrylic plates have been lined with industrial grade vacuum bagging which ensures protection from rainwater in bad weather conditions. Moreover, the LiDAR, GPS, IMU and cameras are IP67 rated by build enabling them to endure extreme weather.

5. Electronics and Power Design

5.1. Overview

The electrical schematics of Zephyr have been designed in such a way that it portrays intelligence, long working hours, safe design and durability. The control section consists of an Electronic Speed Controller (ESC) for the BLDC hub motor control, a FlySky Transmitter for wireless safety operations and the Dell Inspiron laptop as the processing unit. In addition, an Arduino microcontroller has been used to setup intermediate links in between various electrical components.

5.2. Power Distribution System

Zephyr's power system is divided into two parts: the processor powering unit and the Sensor and Control powering unit.

The power system consists of a single 36V Li-ion battery with a capacity of 32Ah. Unaltered 36V is divided into the corresponding sensors and motion unit through a custom designed power board. A DC-DC Converter steps down this 36V to 12V to power the LIDAR and the GPS. The ESCs (motor controllers) take up 36V to power up the motors and the hall encoders. The processing unit has its own independent power source - that is, the battery.

Total Power under full load condition turns out to be 362.5W for the sensors and control unit. So according to battery's amperage, the sensors and motors could run up to 3.1 hours.

Maximum power consumption = 362.5W

Minimum time available = Battery Capacity / Total max power consumption = (36 V * 32 Ah) / 362.5 W = 3.1 hrs

However, this is under the most ideal conditions and in actuality the battery can power the system upto 4 hrs. The processor's battery can run it up to 2.5 hrs under full load condition.

Hence, Zephyr's working runtime is about 2.5 hrs.

The adjacent chart describes Zephyr's power distribution and electronics system:

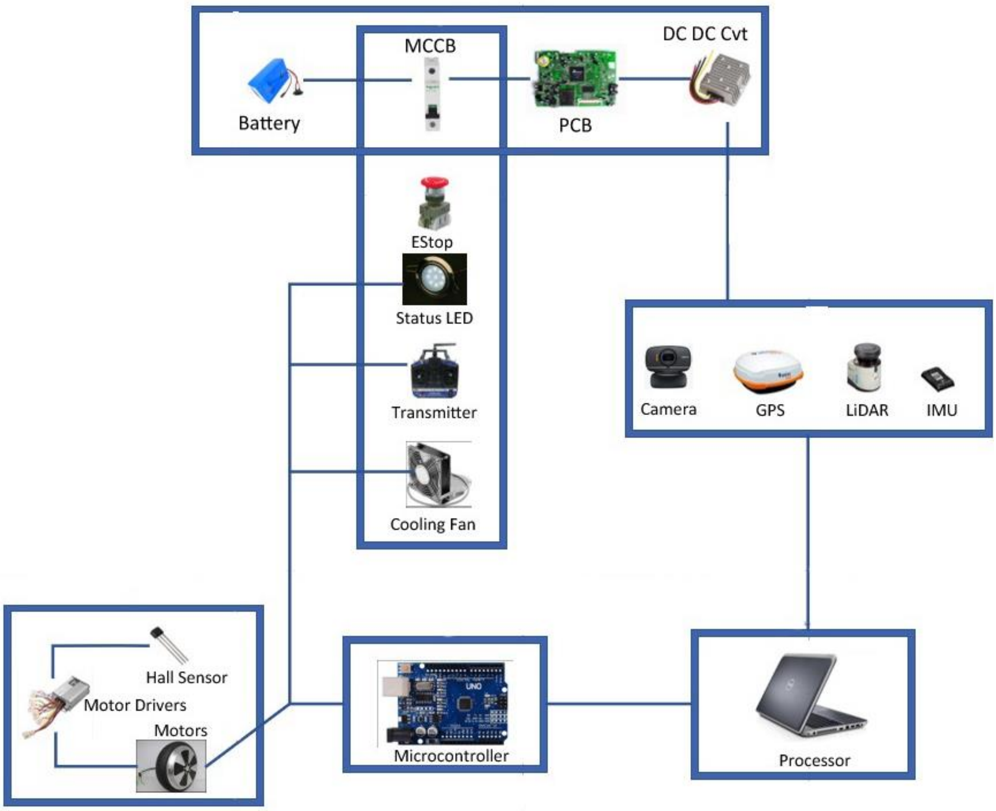

Figure 7 Electronic Suite

5.3. Electrical System

ELECTRONIC COMPONENT	POWER CONSUMPTION	OPERATING VOLTAGE	SOURCE
Sick LIDAR LMS111	8W	12VDC	DC-DC Converter
Sparton AHRS-8 IMU	0.32W	5VDC	Laptop via USB
AtlasLink GNSS	4.5W	12VDC	DC-DC Converter
Segway Hub Motors	350W	36VDC	ESC
Dell Inspiron	9W	19.5VDC	Laptop Battery Pack
Logitech B525 Webcam	5W	10VDC	Laptop via USB

5.4. Vehicle Safety Design Concepts

- Zephyr comes equipped with over current protection at each component level. The sensors are protected with appropriate fuses to avoid over amperage. Further the whole of the electronics suite is protected under a Circuit Breaker which can shield against high currents.
- Zephyr incorporates both hardware and software switching to electric systems. The vehicle comprises of a Mechanical E-Stop placed on the mast and also includes a Wireless Switching system which can be activated through the transmitter in case of emergency.
- The wiring of Zephyr has been done with Teflon coated wires which can sustain temperatures of up to 250° Celsius. This enables Zephyr to function in rugged conditions.
- Zephyr's Health Monitoring System is developed in such a manner that it is user friendly. The battery health and vehicle temperature are displayed on indicative LED strips.

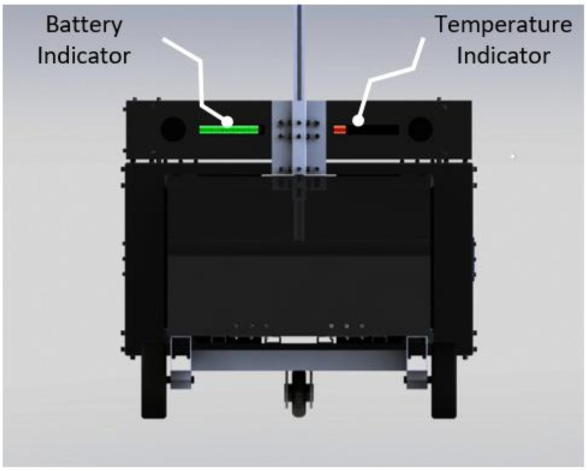

Figure 8 Health Indicators of Vehicle

6. Software Strategy: Navigation

6.1. Overview

The software has been developed using Robot Operating System (ROS) framework which provided a collaborative environment during software development life cycle which enabled us to concurrently design several components of the software and test in isolation. ROS is equipped with hardware abstraction, device drivers, libraries, visualizers, message-passing, package-management which greatly helped us to seamlessly integrate all the components to develop a modular design, made to handle specific tasks that can be modified, replaced, or removed without affecting the function of other nodes.

6.2. Lane detection and Obstacle detection

Vision adds the ability to identify lanes and potholes in the environment. Zephyr achieves this through the use of two Logitech B525 cameras mounted on its mast in a configuration which ensures maximum horizontal field of view. The image feed from the two cameras is stitched using real time panoramic stitching and is further processed using Opencv libraries in C++.

- In order to extract the information about the lanes and potholes from the stitched image, region of interest in the frame is chosen for further processing which eliminates the irrelevant data such as sky's horizon and robot's frame which proves to be constant source of noise. Noise is further reduced by blurring with a Gaussian filter.
- Next, we perform lane segmentation by separating the resultant image into 6 channels red, green, blue and hue, saturation, value and using two channels which exhibit white lanes vividly.
- Using colour segmentation barrel contours are recognized and removed so that the white lines on the barrel are not treated as lanes.
- Adaptive Thresholding is applied in the above chosen image channels with threshold value determined using a light meter installed on the vehicle and the relation between the two values are established during the testing and the calibration phase.
- Two image channels from the previous step still contain certain amount of noise which is completely eliminated by morphological filter.
- After this, the above computed binary images are overlaid on each other to form the single image. This is done so that if one channel does not possess the entire line in field of view then the data from another channel is merged onto it. This makes the vision algorithm robust and tolerant to the variable lighting conditions of the environment
- The above computed image we obtain from the above-mentioned steps gives us a perspective mapping of the 3D environment on a 2D plane which needs to be converted to ground coordinates for mapping procedure. This is done by generating a 'birds-eye-view' of the image using Inverse Perspective Mapping. Here we need not extract the pothole exclusively since the mapping algorithm treats both lanes and potholes (white pixels after Thresholding) as obstacles. Finally, the resultant binary image is fed into the occupancy grid for path planning.

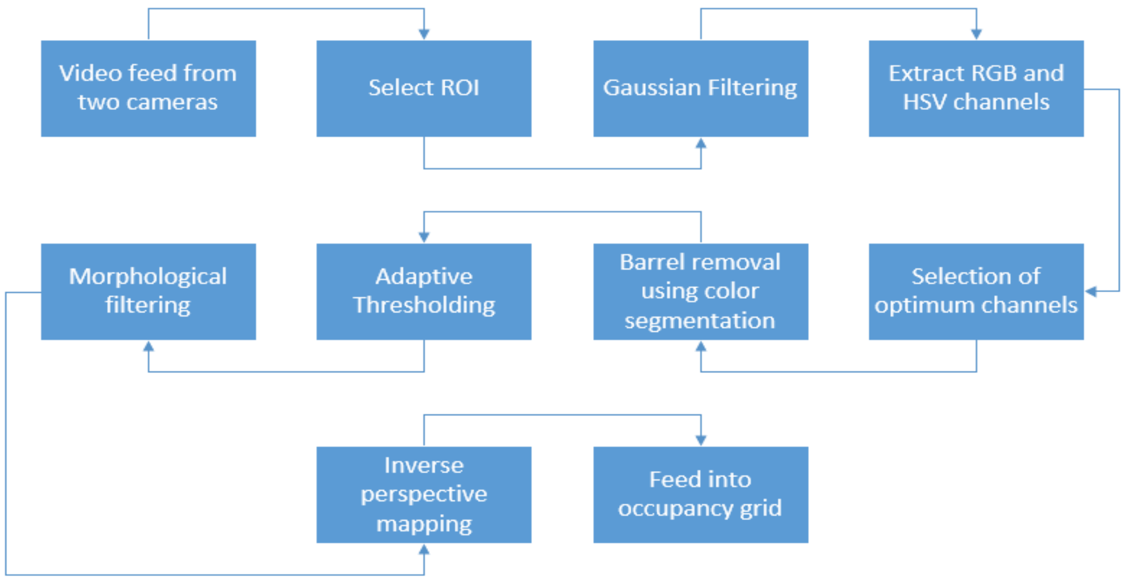

Figure 9 Vision Module Flowchart

6.3. Localisation

Localisation is performed to ascertain the location and pose of the robot with respect to its environment. This ensures that there is good agreement between the robots actual and perceived position and orientation. This is critical to the proper functioning of the navigation module.

Conventional SLAM techniques could not be considered due to the sparse environment encountered at the IGVC course. Hence, an alternative method of sensor fusion and using an Extended Kalman Filter to estimate the current robot state was chosen as the method for localisation. This however, forced us to segregate localization and mapping into individual nodes.

6.3.1. Sensor Fusion And EKF

Fusing sensor data from different sensors like GPS, IMU and Wheel Encoders allows us to localize the robot with high accuracy. The Wheel Encoder and IMU data is initially fed to a preliminary EKF node which outputs high frequency localization data. Additionally, the intermittent GPS data is sent to a separate transformation node before being fed into the final localization node. At this node, it is merged with the output from the first localization node. This ensures that the navigation module always receives high frequency localization data with the GPS data providing only periodic corrections to the localization state vector.

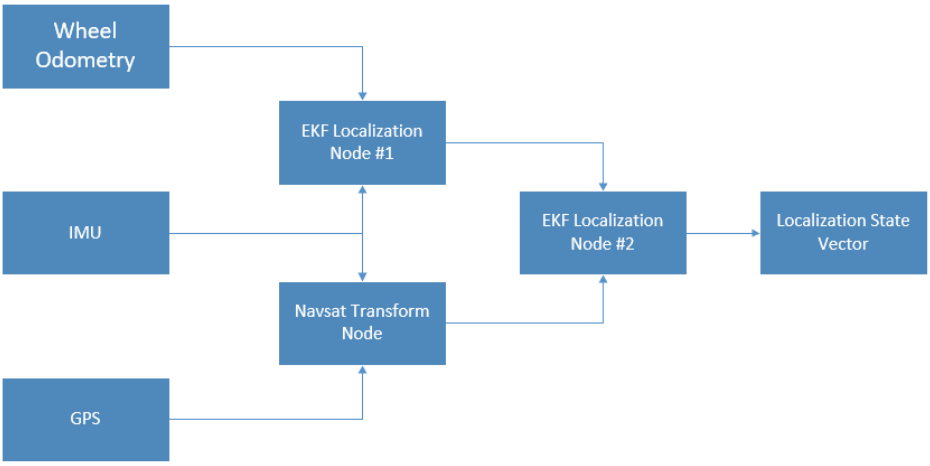

Figure 10 Localisation Module Flowchart

This cascaded Extended Kalman Filter (EKF) is implemented using 2 robot_localisation nodes and a navsat_transform node on ROS. Its implementation is as follows.

6.4. Mapping

The primary objective of mapping was to generate a global costmap in order to implement the move_base navigation node on ROS. Additionally, mapping allows us to visualize the robot's sensory perception and hence it can be used to debug, as well as evaluate the effectiveness of different algorithms.

6.4.1. Global Costmap Generation

A global costmap of the lines and obstacles present on the course must be constructed for utilization by the path planner. Essentially, a costmap identifies obstacles using 2D LIDAR data and maps them in the environment using an occupancy grid. The obstacles on the grid can then be inflated to ensure safer navigation and a more robust path planning.

Furthermore, this obstacle data must be supplemented by the visual line data from the line detection module in order to achieve successful path planning.In order to facilitate this, the visual line data is converted into obstacles. This is done by publishing the vision data in the form of a point clouds. This point cloud data is then converted into obstacle data before being superimposed to the existing costmap using a costmap plugin.

The global costmap data is subsequently passed on to the path planner to implement global waypoint navigation.

Figure 12 GMapping with LiDAR Points

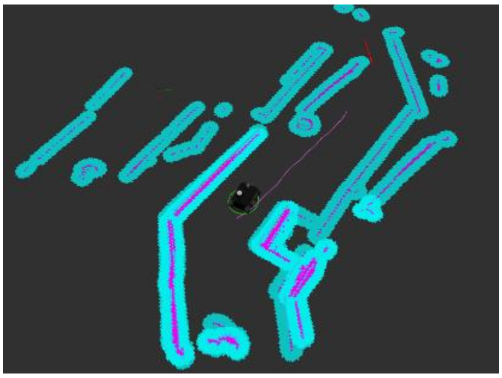

Figure 11 Costmap with Lanes and Obstacles

6.5. Goal Selection and Path Generation

Zephyr bases its decision on planner modules that create the collision-free waypoints in the path to reach the destination point.

The path planning module is divided into a global planner and a local planner, where the first one finds the optimal path with a prior knowledge of the environment and static obstacles, and the second one recalculates the path to avoid obstacles. The global planner requires a map of the environment to calculate the best route for which it subscribes to global costmap. The global planner divides the planner into nodes for each cell but the outcome is not smooth and some points are not compliant with the vehicle geometry and kinematics.

In order to transform the global path into suitable waypoints, the local planner creates new intermediate waypoints taking into consideration the obstacles and the vehicle constraints. So, to recalculate the path at a specific rate, the local planner subscribes to local costmap which is reduced to the grid size of 10X10 with a resolution of 5cm per cell of the surroundings of the vehicle and is updated as the vehicle is moving around. It is not possible to use the whole map because the sensors are unable to update the map in all regions and a large number of cells would raise the computational cost.

Therefore, with the updated local map and the global waypoints, the local planning generates avoidance strategies for obstacles and tries to match the trajectory as much as possible to the provided waypoints from the global planner.

Global planner uses the Dijkstra algorithm to create the global plan to reach the goal point using the global map. This path message is a standard type navigation_msgs/Path.msg which contains the waypoints without the orientation.

Local planner computes local plan with a configurable look ahead distance and estimates the maximum velocity and angular velocity of the vehicle in that region and publishes it on cmd_vel topic to which the PID controller subscribes. PID velocity is responsible for creating the PWM necessary to drive the DC motor. It takes as input the current velocity. The type of message is standard as std_msgs/Float64.msg

In a scenario, when the vehicle is stuck in a dead end then it switches to its recovery behaviour in which it attempts to rotate on its axis to find an escape from that situation. This also proves to be the fail safe in the situation when the sensors generate false positives in the obstacle course or when wheel slips on ground.

7. Failure Points and Resolution

S.NO	FAILURE POINTS	RESOLUTION
1.	Damage to Electrical Couplers and Connectors	• The couplers used in Zephyr easy to remove and new thimbles can easily be crimped as replacement.
2.	Improper PWM actuation to motors	• A filter circuit of appropriate time constant can be installed
3.	Unable to reach goal	• Increase goal tolerance there might be possibility that GPS waypoint coincides with an obstacle. • Check for false positives from LiDAR using Rviz. • Increase the size of global costmap to accommodate the GPS waypoint on it.
4.	Robot revolving on its axis	• Increase yaw tolerance
5.	Jerk motion of the vehicle	• PID constants needs better tuning
6.	Bolts used to fasten extrusions loosen over time	• Use Loctite thread-lockers for permanently fastening critical joints of the primary structure
7.	Bolt heads shear due to interference with surfaces of aluminium extrusions	• Tighten bolts only up to a maximum torque rating
8.	Primary structure not responding as expected due to high compliance	• Keep regular check on the fastening of various chassis members and replace damaged fasteners regularly

8. Simulations

A replica of the IGVC map was created to test out simulations in a virtual environment. This was accomplished using Gazebo as a simulation platform, to represent our vehicle geometry, vehicle kinematics, ground surface texture, height maps, and various IGVC environment features. The sensor data is published on different ROS topics which can be used to test localization, path planning, mapping, obstacle avoidance and other algorithms we are employing. All this computation is visualized using Rviz which also allows easy modification in the behaviour of the vehicle. The simulation proved to be useful because testing is an inevitable step in understanding the cause of errors and improving the vehicle. The recorded data can be disproved in a real environment, thus we can test the vehicle in a virtual environment beforehand.

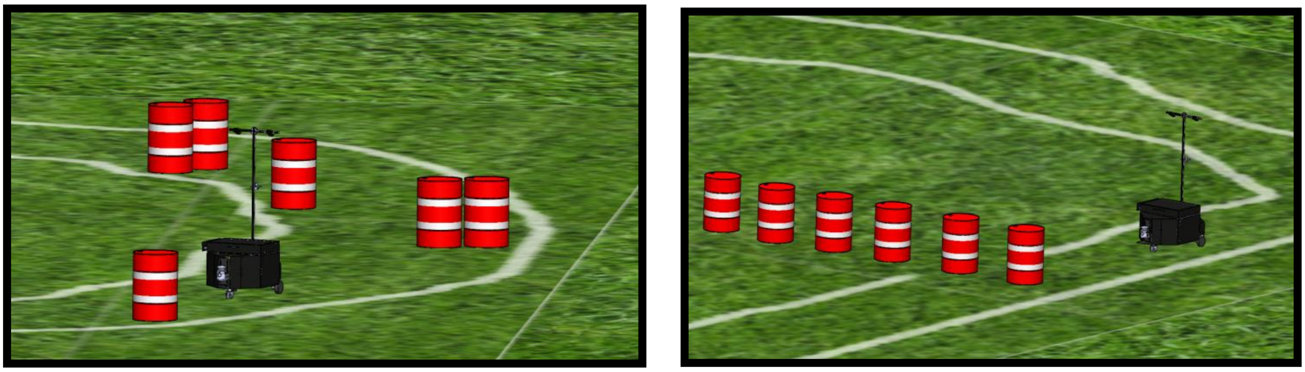

Figure 13 Autonav Simulation

9. Testing

Zephyr was tested in an outside environment that was similar to the IGVC competition layout. The white lines were on the grass with barrels placed throughout provided an ideal pseudo- competition environment to test the vehicle. Outdoor testing was done only when all the modules of the system were operational and independently working desirably.

Mechanical validation was done by performing rigorous tasks by the vehicle such as ramp climbing, wet surface and rough terrain manoeuvring using RC control and even carrying out crash testing to ascertain the mechanical robustness of the system. Electrical testing and validation was done by ensuring all the electronic components are working properly by accessing their data on Rviz and power supply was also monitored using DSO. At software end most of the testing was performed on Gazebo using bag files during unit testing and the physical behaviour was validated against the results obtained from simulation and if the vehicle does not manoeuvre desirably there are many parameters that were tuned to get desirable functionality.

10. Initial Performance Assessments

Zephyr adheres to the general rules requirements of IGVC. The following summarize the various physical parameters that have been successfully validated during numerous testing sessions:

- Various sensors performed well in their working capacities and provided expected input in real-time test runs.
- Maximum speed of 3.5 mph during testing
- The estimated battery life is about 1.5 hour on continuous usage
- Ramping ability has been rigorously tested over multiple inclines of up to 15-degree inclination.
- Software framework has been validated by successful avoidance of obstacles which are to be present on the competition track.
- Simulations are coherent with on-track testing results.

Zephyr has currently achieved the various competition requirements like way point navigation, obstacle avoidance and path planning to a great extent and hopes to do the same at the competition.