DELHI TECHNOLOGICAL UNIVERSITY

CAPELLA

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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 2019 Intelligent Ground Vehicle Competition has been significant and equivalent to what might be awarded credit in a senior design course.

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1 Introduction

Zephyr is the autonomous ground vehicle team of Delhi Technological University, India. We are a group of highly driven and motivated polymaths who develop, envision and engineer cutting-edge technology in the field of autonomous mobility. It is with great pleasure that we introduce our latest brain child *CAPELLA* in Intelligent Ground Vehicle Competition 2019. We have developed Capella–a smart, autonomous, differentially-steered vehicle which can manoeuvre within specified lanes while dodging obstacles and potholes to reach a goal guided by GPS waypoints.

2 Team Organization

We believe that team work is at the heart of any great achievement. Our goal was not just to develop an autonomous vehicle but to build an environment which nurtures team and individual's growth simultaneously. To ensure that the team functions as a well-oiled machine, we ascertained that there should exist good communication among members and effective knowledge transfer so that very member shares a common vision.

TEAM MEMBER	MAJOR	ROLE
Adhiraj Singh	Computer Science	Battery Management/ Perception System
Divye Bhutani	Software Engineering	Mapping/ Path Planning/ System Integration
Sahil Bhatia	Engineering Physics	State Estimation/ Logistics
Tinandumoy Bose	Mechanical Engineering	Operations
Yusuf Ali	Mechanical Engineering	Design/ Fabrication/ Control Systems

3 Design Assumptions

After last year's IGVC, we were proud of how we performed and at the same time we reflected on our mistakes to conceive an exhaustive post competition analysis to acknowledge our errors and devise a strategy for the upcoming year.

We adopted a pragmatic approach for this year's competition which became the backbone of our design philosophy - aiding us to determine realistic design goals.

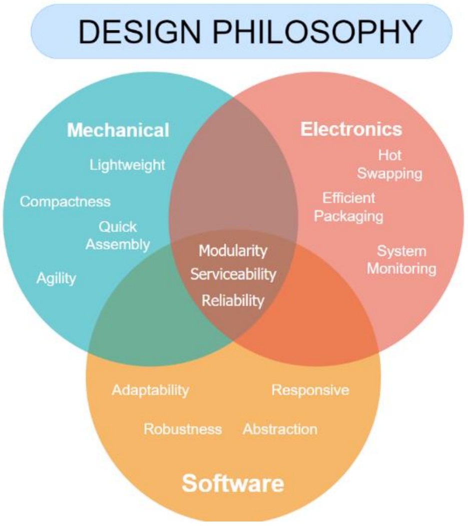


Figure 1: Fundamental Design Philosophy

4 Design Process

Right from the inception of the project we ascertained that we must perform rigorous testing at every level which led us to adopt the V-testing model for Capella. The V-Model demonstrates the relationships between each phase of the development life cycle and its associated phase of testing. The horizontal and vertical axes represent time or project completeness (left-to-right) and level of abstraction (coarsest-grain abstraction uppermost), respectively. Deliverables expected from each development phase were identified and, in parallel, test strategy, test planning and test cases were formulated which ensured that the software meets the functional and non-functional requirements specification captured during the requirement identification phase. For this purpose, effective and critical project management techniques were implemented. Project tracking sheets were developed and maintained throughout the project. This ensured a holistic development of the team members and enhancing their technical and managerial acumen to tackle challenging real-world problems.

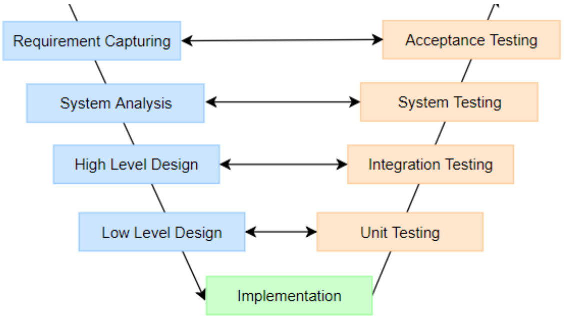


Figure 2: SDLC and STLC

5 Innovations

- **Modularity:** Capella has a highly modular structure in it's mechanical, electrical and software architecture. This enables easy troubleshooting and maintenance of the vehicle during rigorous testing runs. A multitude of modular features have been discussed in the subsequent sections.

- **Transportability:** Capella's mechanical design enables it to be quickly disassembled into four discrete compartments. This prominent aspect of the mechanical design facilitates the effortless and economical transportation of the vehicle to the competition in a standard suitcase that is permitted over international flights.

- **Quick Assembly:** The modularity and transportability of Capella also facilitate its expeditious assembly from scratch. Capella can be assembled into its typical working state in well under 30 minutes – minimizing the downtime during transportation and supplementing serviceability.

- **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. Rigorous track testing ensured that both sensors were optimally placed with respect to Capella's body.

- **Telemetry:** To implement over-the-air programming into Capella's software architecture, a highly robust telemetry system has been conceived to ensure remote access to the vehicle. This helps the user to remotely monitor and dynamically reconfigure the vehicle's critically performance parameters.

- **Payload Accessibility:** From previous experience, it was ascertained that the payload had to be easily removable from the vehicle's mainframe to ensure easy transportation at the competition site during testing runs. Industrial standard LC-80 latch clamps have been used to facilitate quick assembly/disassembly.

- **Health Monitoring System:** Capella is equipped with an intelligent vehicle monitoring system which displays the real-time signals of critical parameters including the on-board battery voltage, temperatures of various hotspots, voltage surges across crucial electrical components and sensor data for quick troubleshooting. The various parameters are viewed on the Visual Display Unit (VDU) which is mounted on the camera mast - alongside the kill switch.

6 Cost Estimate

ITEM	SPECIFICATION	ORIGINAL COST	COST TO TEAM
Processing Unit	NVIDIA Jetson AGX Xavier	$2500	$1,600
LiDAR	SICK LMS111	$5500	$4700
IMU	Sparton AHRS-8P	$1840	$1840
GPS	AtlasLink GNSS	$4900	$4425
Motor Driver	Cytron Smart Drive Duo-30	$80	$80
Transceiver Module	Bullet M2HP	$110	$110
Motors	Geared DC brushed motor	$35	$35
Wheel Encoders	Orange 400 PPR Optical Rotary Encoder	$40	$40
Jetson Network Adapter	Intel wireless 8265	$25	$25
Antennas	Ipex MHF4 Antenna	$25	$25
Status Light	Tower light	$13.5	$13.5

Kill switch	Mechanical universal standard	$1.5	$1.5
Camera	Logitech B525	$80	$80
Camera	Logitech C930e	$140	$140
Microcontrollers	Arduino	$70	$70
Wireless Transceiver	Flysky	$55	$55
Cooling Fan	Sunon	$25	$25
Raw Material	Generic	$150	$150
Materials required	Generic	$180	$180
TOTAL		$15849	$14875

The project was undertaken in December, 2018 and since then immense time and effort has been devoted to IGVC Project. On an average each team member has spent **70 hours per week**, amounting to **total 1050 man-hours** since the inception of the project.

7 Mechanical Design

7.1 Overview

Following on from last year's design philosophy, Capella's mechanical design revolves around three basic design considerations that enable it to produce the best on-track 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

At every stage of the design process, it was emphasized that the entire structure should be highly modular in nature. In addition, it must be easy to assemble and transport enabling highly reduced downtimes between testing and transporting sessions. (Figure 3)

Capella's body has been designed such that it can be readily divided into four parts – facilitating transportability and modularity. The front compartment securely houses the GPS, IMU, LiDAR and payload. It also constitutes Capella's drivetrain assembly including the optical encoders. LC-80 latch clamps have been used to provide quick accessibility to the payload to assist easy transportability at the competition site.

The rear compartment houses the castor wheel and the network router which is a crucial constituent of the telemetry system onboard Capella.

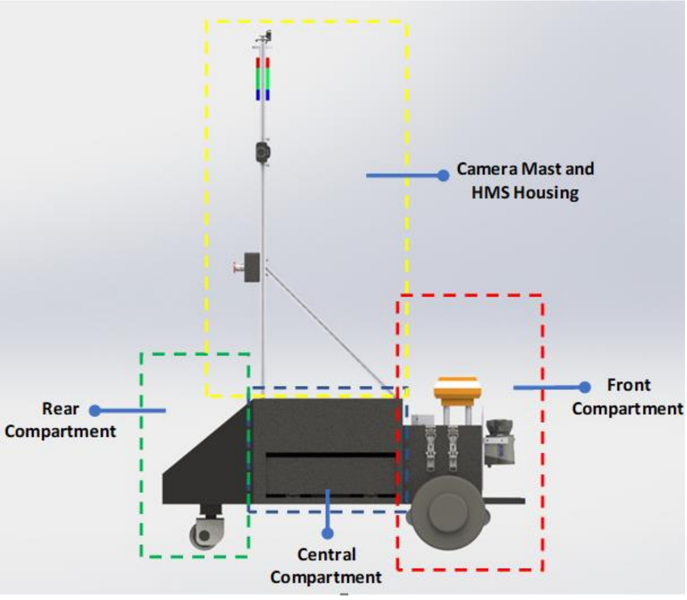


Figure 3: Compartmental Modularity in Capella

Figure 4: Upper and Lower Level Bifurcation in Central Compartment

The central compartment is segregated into two compartments. The lower compartment comprises of the battery and power distribution unit and serves as a mounting location for the MCBs. The upper compartment houses a couple of electronic enclosures, the main processing unit, the bullet transceiver and a USB hub. (Figure 4)

The camera mast houses the adjustable mounts for the cameras, the status light, the kill switch and the visual display unit (VDU).

7.2 Frame and Structure Design

Capella's dimensions adhere to the minimum geometric constraints stipulated by the competition which ensure high packaging efficiency and improved manoeuvrability of the robot. In addition, it has been critically focused upon to position Capella's centre of gravity as close as possible to the ground to mitigate toppling tendency and increase overall stability of the robot. Moreover, Capella 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 Capella to revolve about the vertical axes passing through motors. The wheel radius has been increased to 10" as the former 5.5" inch tires were highly susceptible to wheelspin. (Figure 5)

Figure 5: Capella Frame Structure

7.3 Material Selection

In an attempt to carry forward previous year's material selection strategies, the team decided to fabricate Capella's lightweight structure using 20 mm x 20 mm T-slot aluminium extrusions in conjunction with 2mm thick aluminium sheets. This also enabled the team to cut down on material procurement costs as raw material from last year's vehicle could be critically salvaged – leading to a massive reduction in budget.

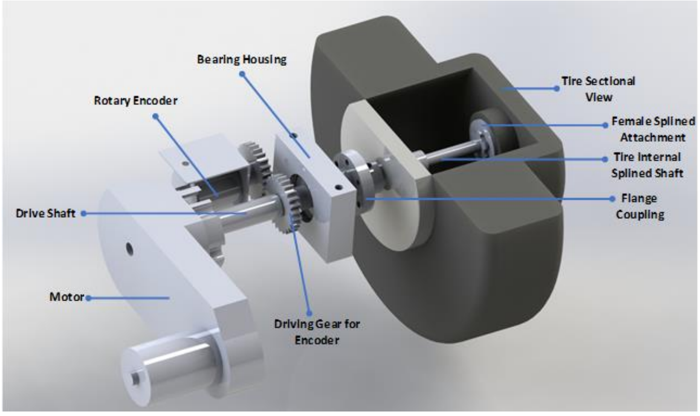


Figure 6: Drivetrain Assembly Components

Extrusions have been considered for erecting the primary structure of the vehicle as they have a considerably higher section modulus – providing increased bending stiffness combined with aluminium's lightweight properties. Moreover, aluminium extrusions are an industrial standard and are an economic and accessible option from the standpoint of the market. The reinforcing aluminium sheets were fabricated to the required dimensions using laser-cutting process. All material considerations have been carried out using thorough structural analysis using ANSYS 16.0. To ensure that Capella remains aesthetically appealing, HDPE sheets have been used for covering the entire primary structure.

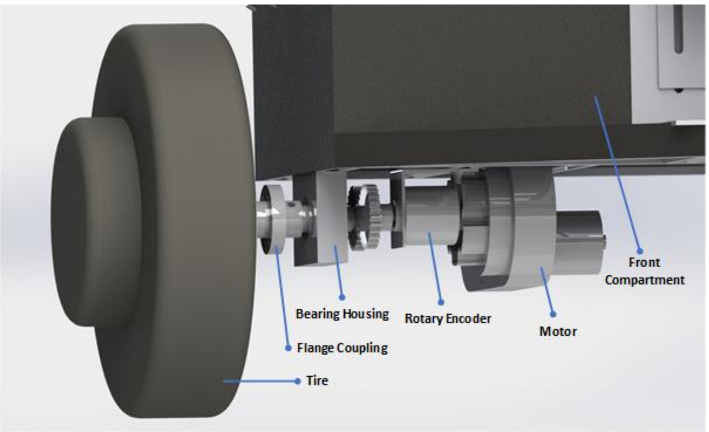


Figure 7: Flange coupling attachment for custom tires

The afore-mentioned choice of materials enabled Capella to weigh in at under 30 kgs – which is considerably lighter than most other counterparts attending the competition.

7.4 Drivetrain

To improve stability and minimize toppling tendency, Capella incorporates two driving wheels in the front compartment and a driven caster wheel at the rear for achieving overall stability. The rear wheels are powered by two independent brushed DC motors. Each DC motor houses an internal gear box to achieve the required gear reduction. The bearing housing and drive shaft were manufactured in-house on a lathe machine. (Figure 6)

To facilitate easy assembly and transportability, the tires are attached to the drive shaft using flange couplers and grub screws. The 10” tires have been salvaged from previous year’s BLDC hub motors by removing the internal stator and fabricating a splined shaft to transmit power from the drive shaft to the tires. Also, a 1:1 geared drive is used to transmit the drive shaft’s motion to the optical rotary encoder. (Figure 7)

7.5 Adjustable LiDAR Mount

The sensor mounts for the LiDAR and cameras have been designed such that their orientation with respect to Capella’s structure can be altered so as to permit on-track calibration. The LiDAR’s mount allows for a total variability of 30 cm in its height from the ground.

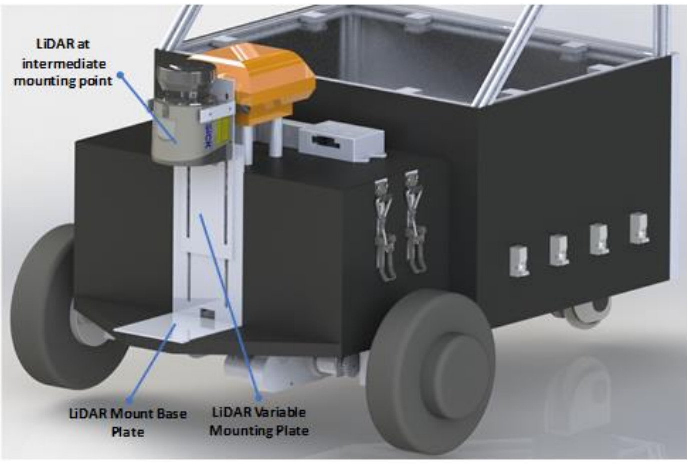


Figure 8: LiDAR Mount extended upwards

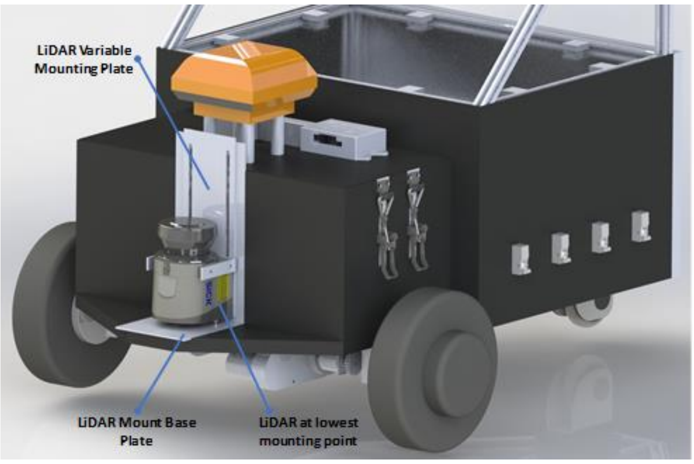


Figure 9: LiDAR Mount lowest position

7.6 Payload Accessibility

Onboard Capella is a quick-release mechanism for instantly placing the payload into and out of the front compartment of the vehicle.

Transporting the vehicle when the payload is placed in the vehicle becomes a tedious task at the competition site. Hence, the quick release mechanism has been incorporated in order to facilitate easy transportability of the vehicle at the competition. Industrial grade LC-80 latch clamps have been used for the aforementioned purpose.

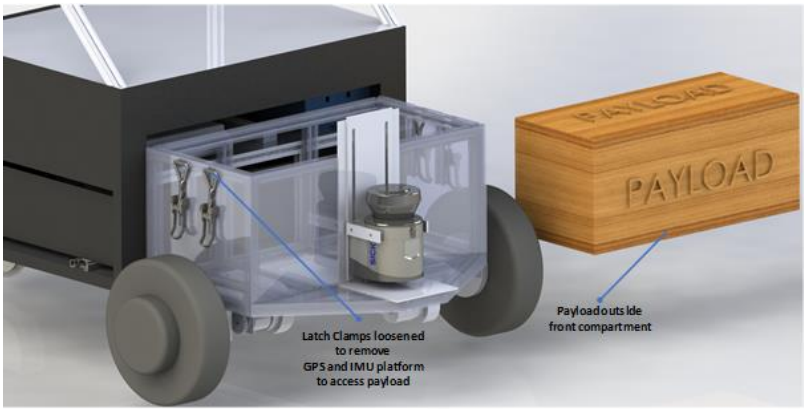


Figure 10: Payload removed from front compartment

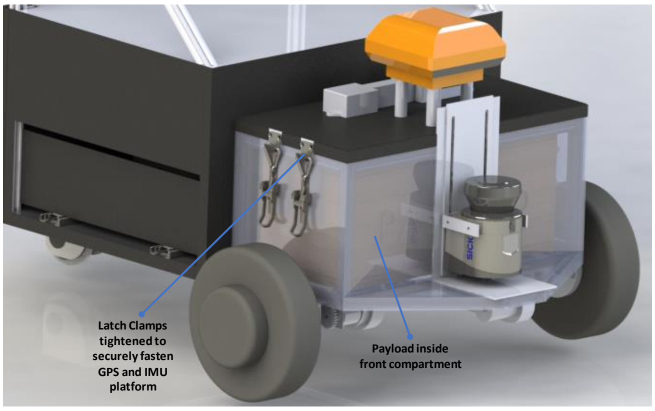


Figure 11: Payload inserted into front compartment

7.7 Suspension

Upon a critical analysis of the performance of last year's competition vehicle and deliberations over suspension systems of various vehicles that have performed exceedingly well in the competition, it has been ascertained that incorporating a suspension system in the vehicle structure does not provide magnanimous benefits in lieu of the added complexity in design.

7.8 Weather Proofing

Acrylic plates form Capella'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 HDPE plates have been lined with industrial grade Flex Seal rubber sealant coating 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.

8 ELECTRONICS AND POWER DESIGN

8.1 Overview

The electrical schematics of Capella have been designed in such a way that it portrays intelligence, long working hours, safe design and durability. The control section consists of the Jetson AGX Xavier as the main processing unit, Cytron SmartDrive Duo motor driver for the two motors, a FlySky Transmitter for wireless safety operations. In addition, an Arduino microcontroller has been used to setup intermediate links in between various electrical components. A network transceiver and router have been incorporated for easy and efficient communication between the vehicle and the base station.

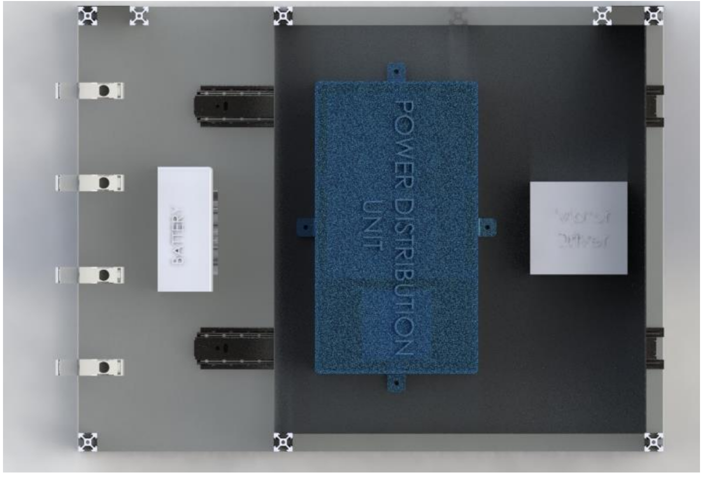


Figure 12: PDU placed in lower level central compartment alongside battery and motor driver

8.2 Power Distribution System

- The Power Distribution Unit (PDU) is a highly modular unit which encapsulates the entire low-level electronics circuitry responsible primarily for power distribution.
- The PDU is a highly serviceable and accessible module of the electrical architecture – implementing reliable hot swapping techniques and efficient packaging.
- A multitude of safety precautions like Over-Under Voltage Protection, Reverse polarity Protection, Resettable Fuses of appropriate values have been incorporated into the PDU.
- The PDU is placed in a highly accessible "PDU Cage" which can be drawn out of the vehicle's body for quick troubleshooting. This enables the user to achieve reduced servicing downtimes. (Figure 12)
- The power distribution system consists of a single 36V Li-ion battery with a capacity of 4.4Ah. Switching stepdown DC-DC Converter are used to convert the voltages with an efficiency of more than 96% into regulated 24V, 19V, 12V, 5V for the different components of the electronics suit.
- This format of the PDU enable prevention, easy detection and henceforth increase the whole robustness of the entire vehicle.
- The wiring of Capella has been done with Teflon coated wires which can sustain temperatures of up to 250° Celsius. This enables Capella to function in rugged conditions without any power loss.
- Total Power under full load condition turns out to be 79.32W for the sensors and control unit. So according to battery's amperage, the sensors and motors could run up to 1.9 hours.

The following chart describes Capella's power distribution and electronics system:

Electronic Component	Power Consumption	Operating Voltages
Nvidia Jetson AGX Xavier	28.5W	19V
Sick LiDAR LMS111	8W	12V
AtlasLink GNSS	4.5W	4.5V
Bullet M2hp	12W	12V
Motors	20W	12V
Tenda 150Mbps Router	4.5W	9V
Total Power Consumption	77.52 W	

Specification	Value
Battery Capacity	36 V * 4.4 Ah
Max Power Consumption	77.52 W
Minimum Battery Cycle Life (Ideally)	1.9 hrs
Actual Minimum Battery Cycle Life	1 hr
Recharge Rate	45 min

Hence, Capella’s working runtime is about 1 hr.

8.3 Electrical Suite Description

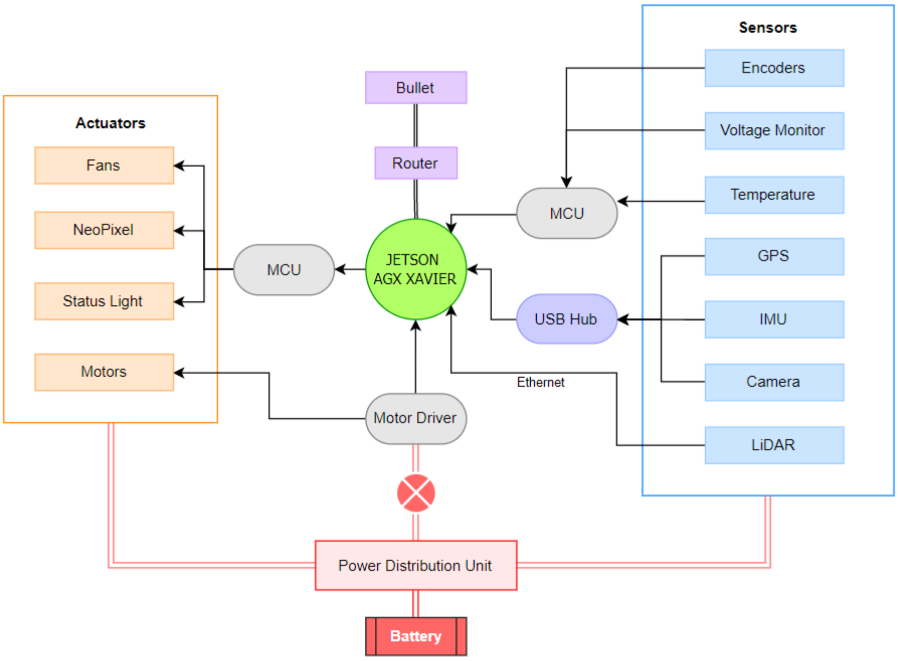


Figure 13: Capella’s Electronic Suite

8.3.1 Jetson AGX Xavier

The main processing unit of Capella is the Nvidia Jetson AGX Xavier. It handles all the High-level algorithms and processes. The microcontroller is also connected to this and is handled using custom python scripts. It runs Ubuntu 18.04. It runs on 19 volts and rarely needs more than 1.5 Amps.

8.3.2 Cytron Smart Drive Duo-30 Motor Driver

This motor driver is designed to drive medium power brushed DC motor with current capacity up to 80A peak (few seconds) and 30A continuously, each channel.

8.3.3 Sick LiDAR LMS111

Mounted on the front compartment of the vehicle, the Lidar uses class 1 lasers to accurately pinpoint objects over a range of 270° with a scanning frequency of 25 Hz.

8.3.4 AtlasLink GNSS

AtlasLink multi-GNSS, multi-frequency smart antenna is preconfigured to receive corrections from Atlas GNSS global correction service. The output frequency of the data signal is 10 Hz and it functions at a baud rate of 19200 bps.

8.3.5 Orange Rotary Encoders

Orange 400 PPR (Pulse Per Revolution) Incremental Optical Rotary Encoder is hi-resolution optical encoder with quadrature outputs for increment counting.

8.3.6 Spartan AHRS-8P IMU

It is capable of sensing the dynamic heading, dynamic pitch & roll and its acceleration with a update rate(sample/sec) of 100 and a baud rate of 115200 baud rate. It also transmits data over the serial bus.

8.3.7 Logitech C930e camera

This camera is specialized for delivery of clear videos at 1080p resolution, even at low-light conditions. Apart from its advanced video graphic capabilities it has a wide 90- degree field of view.

8.3.8 Ubiquiti Bullet M2HP

The Ubiquiti Bullet M2HP airMAX Wireless Radio is ideal for long-distance links and it is capable of 100Mbps+ real TCP/IP speeds over multi-km distances. The Ubiquiti Bullet M2 HP comes with up to 600mW of power and enhanced receiver design. It works on a frequency of 2.4GHz. it is powered through a passive power over ethernet module.

8.4 Safety Devices and Integration

8.4.1 Health Monitoring System:

- Capella comes equipped with features which let the user easily detect and troubleshoot potential electrical system failure points. The Over-Under Voltage protection using operational amplifiers LM358 as voltage monitors has been incorporated for all system components.
- The sensors are protected with reverse polarity protection using MOSFETS in order to avoid errors while assembly. Furthermore, the entire electronics suite is protected under appropriate resettable fuses which can shield against high currents.
- Any diversion in the normal working of the PDU or electronics system would result in an error being displayed from the extensive list of errors using a strip of LEDs on the visual display unit.
- Temperature sensors have been installed at various hotspots for thermal monitoring. The real-time signal of the sensors is used to actuate cooling fans to ensure temperatures remain within safe limits. This data is also displayed on Visual Display Unit.
- Capella’s Health Monitoring System is developed in such a manner that it is user friendly. The battery capacity, vehicle temperature and other indicators like Over-under voltage warning are also displayed on indicative LED strips. To facilitate quick debugging, the output of the wheel encoders is also visualised.

8.4.2 Emergency-Stop:

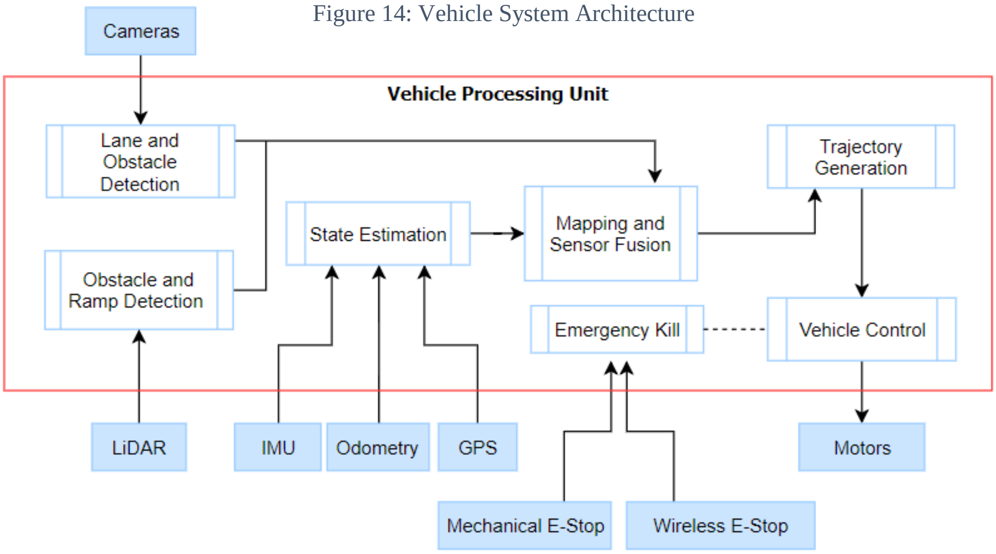
Capella incorporates both hardware and software switching to electric systems. The vehicle comprises of a Mechanical E-Stop placed on the mast and also includes a Wireless Switching system based a FlySky Transmitter-receiver paired up with an Arduino Nano which can be activated through the transmitter in case of emergency.

9 Software Strategy and Design

9.1 Overview

In this section an insight is given in the full setup of the system architecture, perception and state estimation system, including the LiDAR/camera-based mapping & localization system.

Figure 14: Vehicle System Architecture



In addition to the above system architecture, we implemented a Telemetry Unit which enabled the control system of the vehicle to be supervised as well as it can be modified and tweaked during the development and calibration phase. It also provides insight into sensor data like the GPS Co-ordinates as well as system parameters like the battery percentage. Additional data collected in the vehicle, such as video data, can also increase the understanding of the observed processes.

9.2 Obstacle and Lane Detection

Perception system endows the robot with the ability to perceive, comprehend, and reason about the surrounding environment. The key components of a perception system are essentially sensory data processing – from camera and LiDAR, data representation (environment modelling), and computer vision algorithms. In Capella it adds the ability to identify lanes, potholes and obstacles in the environment. Capella achieves this through the use of 1 primary camera, 2 redundant cameras and a LiDAR.

The primary camera provides the front view of the lane, while the two secondary cameras are mounted on the either sides of the vehicle on the camera mast and tracks only a single lane in its view. The purpose of the secondary cameras is to add redundancy in the system to ensure reliable performance of the vehicle when the lanes goes out of the field of view of the primary camera.

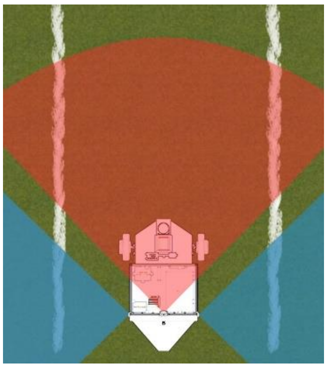


Figure 15: FOVs of camera triad

9.2.1 Algorithm

1. In order to extract the information about the lanes and potholes from the 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.
2. 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.
3. Using colour segmentation barrel contours are recognized and removed so that the white lines on the barrel are not treated as lanes thereby enabling the perception system to perform occlusion handling.
4. Adaptive Thresholding is applied in the above chosen image channels with threshold value determined during testing and calibration phase.
5. Further leftover noise is eliminated by morphological filtering.

6. 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.
7. 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.
8. Here we need not extract the pothole exclusively since the mapping algorithm treats both lanes and potholes (white pixels after Thresholding) as obstacles.
9. Finally, the resultant binary image is then transformed from camera coordinates to world coordinates before they can be merged into the occupancy generated through LiDAR. The conversion from the camera coordinates to world coordinates by figuring out the pixels per meter ratio during the calibration of the camera.

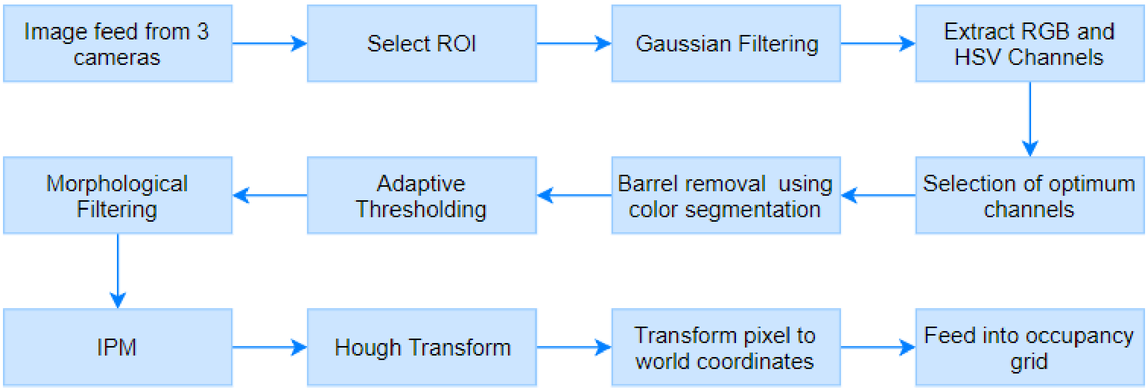


Figure 16: Flowchart for Computer Vision Algorithm

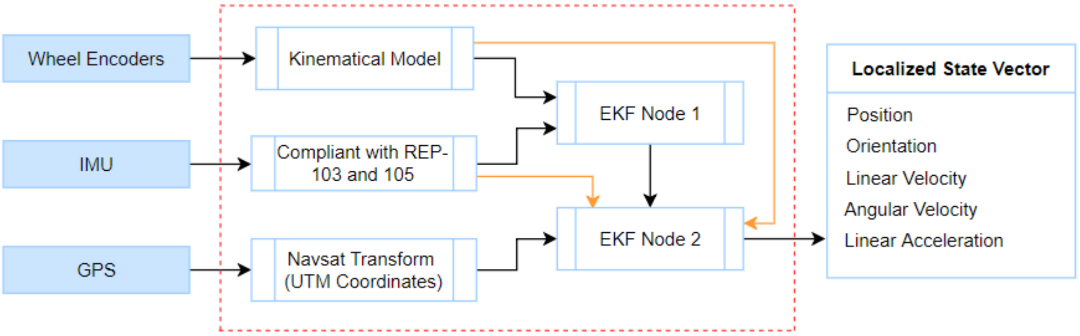
9.3 State Estimation System

State estimation is an essential part of any mobile robotic application as it enables the robust operation of other system components. Several sensors are fused to estimate the pose and velocity of the ground vehicle.

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.

Wheel encoders produce number of counts which is fed into the kinematical model developed for the vehicle which computes the odometry information of the vehicle with respect to its initial world coordinate (referred as “odom” frame in ROS). It contains the position, orientation, linear and angular velocities. This odometry data is fused with the IMU data after making their respective outputs are made compliant with REP – 103 and 105 standards.

Figure 17: Cascaded EKFs



GPS is added to the system to add reference for waypoint navigation and further enhance the position estimate of the vehicle. GPS produces data in the form of latitude and longitude which complexify the localisation of the vehicle on the map generated. So, to mitigate through this problem and we must convert the GPS coordinates to UTM coordinates which is a 2-D cartesian coordinate system. The state vector defined by 15 parameters are obtained by state estimation system are position, orientation, linear velocities, angular velocity and linear accelerations.

9.4 Map Generation

The maximum range of the perception sensors limits the length of the vehicles path planning horizon. This problem can be overcome by mapping the track and localizing the vehicle within it. Mapping generates a global costmap of the environment as the vehicle traverses in its surroundings. We choose to use FastSLAM, a Rao-Blackwellized particle filter-based SLAM method. It was implemented by using gmapping package available for ROS. This takes input of the localized state vector from the state estimation system and the data from LiDAR, fuses it into an occupancy grid which is later supplemented with the data computed from the perception system before injecting it into the navigation module.

9.5 Goal Selection and Path Generation

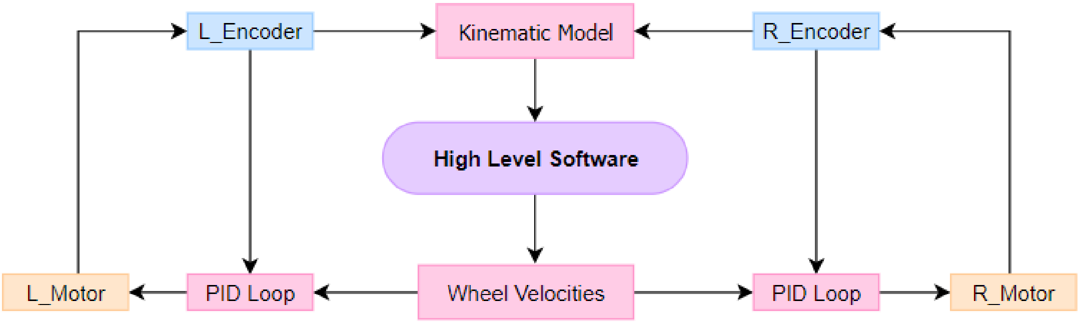
Capella bases its decision on planner modules that create the collision-free waypoints in the path to reach the destination point.

- 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.
- 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 or it will clear the costmap after a certain timeout threshold defined.

9.6 Vehicle Control System

Low level control system of the vehicle is based on closed loop feedback control – PID controller. Capella uses two PID loops, one for each wheel. The target velocity for the vehicle is generated by the higher-level software and is disintegrated into wheel velocities and fed in the controller. The feedback is received from the highly precise wheel encoders, which not only provide feedback to the controller but also publishes the raw data for odometry updates.

Figure 18: Low-level Control System



10 Description of Failure Modes, Failure Point and Resolution

10.1 Vehicle Failure Modes and Resolution

S.NO	FAILURE MODE	RESOLUTION
1.	Unable to reach goal	• Increase goal tolerance there might be possibility that GPS waypoint coincides with an obstacle.
2.	Robot revolving on its axis	• Increase yaw tolerance
3.	Jerk motion of the vehicle	• PID gains needs better tuning
4.	Noise data in camera perception	• Re-tune thresholds manually according to the ambient light conditions
5.	Obstacles are not detected in the map generated	• Increase the particles in the filter • Lower the occupancy threshold values

10.2 Vehicle Failure Points and Resolution

S.NO	FAILURE POINTS	RESOLUTION
1.	Damage to Electrical Couplers and Connectors	• The couplers used in Capella easy to remove and new thimbles can easily be crimped as replacement.
2.	Odometry data is not coming reliably	• Check if the grub screws on the motor shaft are tight • Check if the encoder gear meshes correctly with the shaft gear
3.	Motor transferring drive intermittently	• Check whether mounting points on motor are intact • Check whether coupling points at driveshaft-motor interface have enlarged over time
4.	Vehicle stuck and drive not being transferred to tires	• Check if grub screws are loosened • Apply thread locker to grub screws for better fastening
5.	Power Failure	• Check whether LM323 op-amp damaged • Check whether buck converter damaged

11 Simulations

Gazebo was used in combination with a dynamic model written in python to simulate various features of the vehicle. It played a central role in supporting the designing of software architecture in the initial stages of implementation when the hardware was parallelly in development. The simulation also proved to be a useful tool for preliminary controller tuning. Rviz was used in conjuncture to visualize and debug the system and plan testing strategies for the system by recognizing the points of failures that might occur when we work in real world environment.

Capella's structural frame has been validated using FEA techniques for the applied loading on the vehicle. ANSYS 16.0 FEM software package has been used for the same. Simulation results show that the maximum deformation under critical loading is 0.14931 mm – which is a considerably small value. Furthermore, the maximum value of equivalent stress is found to be 96.976 MPa. The tensile strength of aluminium 6061 alloy is 280 MPa which gives us a factor of safety of 2.89. Hence, Capella's structure has been designed well within working limits.

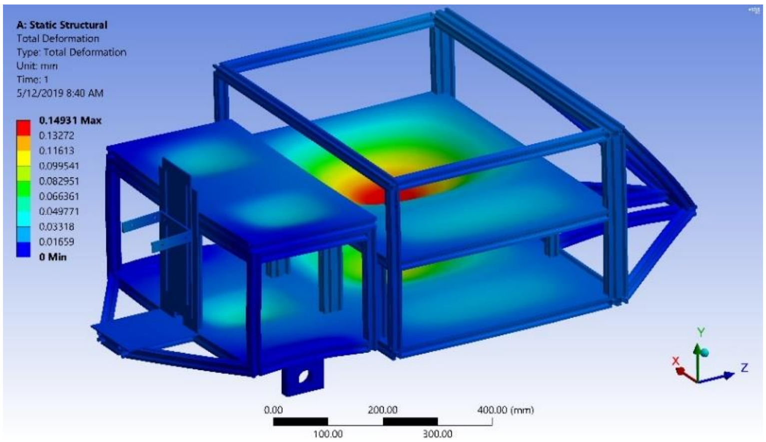


Figure 19: Vehicle Structural Analysis Deformation Distribution

12 Performance Testing

Capella was tested in an outside environment similar to the IGVC competition in terms of track layout. The white lines that were marked on the grass and intermittently-placed barrels provided an ideal pseudo-competition environment to rigorously test the vehicle. Outdoor testing was carried out only when all the modules of the system were independently operational and working desirably upon integration.

Mechanical validation was done by performing rigorous tasks such as ramp climbing, wet surface and rough terrain manoeuvring using RC control. Sudden manoeuvres were carried out to ascertain the mechanical robustness of the system.

Electrical testing and validation were done by ensuring that each electronic component and sensor worked as desired by analysing their signals on Rviz. The integrity of the power distribution system was monitored using a digital serial oscilloscope.

13 Initial Performance Assessment

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

- Various on-board sensors performed well in their working capacities and provided the expected input in real-time testing sessions.

- A maximum speed of 4 mph was achieved during testing.

- The estimated battery life is about 1.5 hour for a routine testing session.

- Ramping ability has been rigorously tested over multiple inclines of up to 15-degree in inclination.

- Software framework has been validated by successful avoidance of obstacles which are to be present on the competition track.

Capella has achieved the various competition requirements like way-point navigation, obstacle avoidance and path planning to an acceptable extent and hopes to develop on the same before the competition.