Autonomous/Driverless Acceleration and Skidpad Analysis for Formula Student Electric Vehicle

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Statement of originality

Except for those parts in which it is explicitly stated to the contrary, this project is my own work. It has not been submitted for any degree at this or any other academic or professional institution.

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Highlights

- The thesis aims at creating a roadmap for the autonomous cars in formula student competition.
- Different sensor setups are analyzed based on competitor's analysis and the setup, most suitable to OBR FS electric car is proposed.
- Acceleration and skidpad events are particularly discussed because of the changes in future of competition.
- An MPC and Stanley controller is used to control the steering of the car. Results of MPC controller are discussed in detail.

Abstract

The aim of the project is to develop a framework and decide the setup of the sensors and propose a suitable control strategy that suits our needs the most based on the complexity, cost, performance and ease of implementation.

The thesis provides a roadmap for the autonomous vehicles in formula student. This would include decoding the autonomous competition for future changes, automated system required for making the OBR FS electric vehicle autonomous and deciding on control strategy for the dynamic events, acceleration and skidpad. While the acceleration event is straightforward with no steering changes, the skidpad (figure of 8) event requires quick response.

The thesis compares various autonomous systems used by the teams in formula student. A database of subsystems used is created and studied. A points-based matrix system is employed for making an educated and logical decision on the selection of each subsystems for the OBR EV Autonomous Vehicle. A Motion Predictive Controller (MPC) is built for the lateral control of the vehicle on the skidpad course. The controller is built in Simulink using the automated driving system toolbox and the tracks are designed in the Driving design scenario app of MathWorks. Alternative options on certain aspects of the Project are also discussed and presented.

Acknowledgement

I have received a great deal of support and assistance, throughout the writing of this thesis. I would first like to thank my supervisor, Gordana Collier, for her guidance and support both for this project and my degree.

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Abbreviations Used

ASMS	Autonomous System Master Switch
RES	Radio Emergency Stop
FSG	Formula Student Germany
OBR	Oxford Brookes Racing
AI	Artificial Intelligence
VCU	Vehicle Control Unit
LiDAR	Light Detection and Ranging
RADAR	Radio Detection and Ranging
GPS	Global Positioning System
IMU	Inertial Measurement Unit

1. Introduction

Formula Student is a well-known competition among the students and the automotive and motorsport industry. There is very intense competition between the teams who compete against each other on various aspects to come out on top of the other. In such an environment it would be vital to get a head start and start as early as possible. Teams not only have to put together a system but also have to justify the decisions made and systems chosen to win the static events.

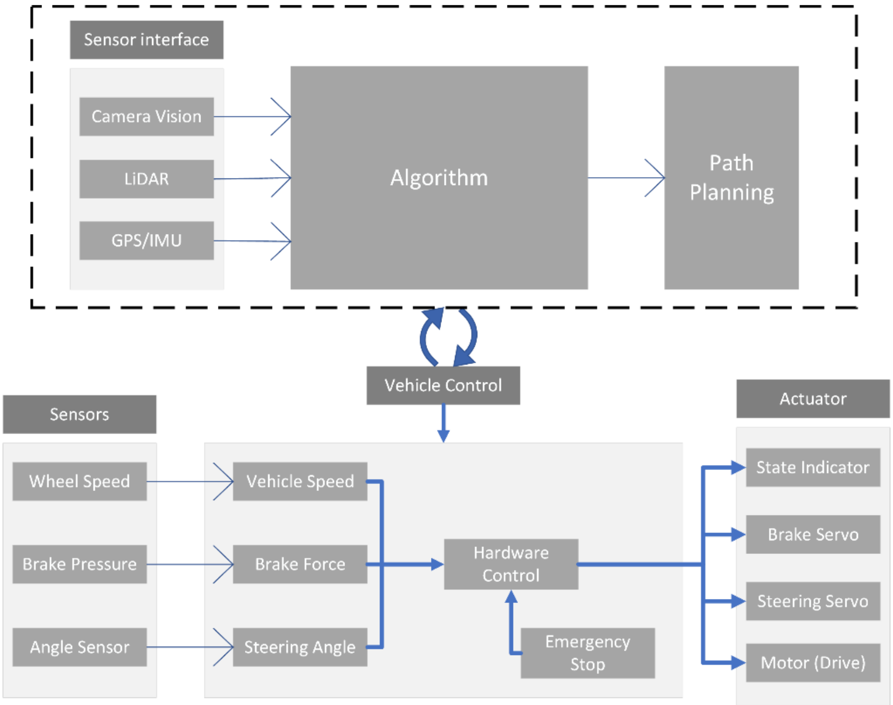


Figure 1: Autonomous Vehicle's Requirement

The basic structure of an autonomous system is represented in the flow chart above. To make the car driverless, all the systems have to interact and integrate with each other. The hardware control, controls vehicle speed, braking and steering angle by sensing wheel speed, brake pressure and angle sensor and actuating the motor drive, brake servo and steering servo. Emergency stoop is also linked to the hardware control.

A look at the comparison between a human driven car and an autonomous vehicle with different configurations is presented below. This gives a basic idea of where each individual system lies and from the table it can be seen that the desired level of autonomy cannot be achieved with just one sensor on board. This indicates that the autonomous system required for our purpose would need to be have two of the vision and detection sensors.

It is also desired to keep the system simple and within the budget, this can be achieved by using camera for vision and LiDAR for accurate detection. LiDAR is also better than RADAR in low light object detection. It is also worth noting that Lidar is better at edge detection and object classification. Even though radar is better at visibility range and poor weather performance is better as well, but under heavy rain it is highly unlikely that the formula student car is run.

Performance Aspect	Human	AV		
		Radar	LiDAR	Camera
Object Detection	Good	Good	Fair	Good
Object Classification	Good	Poor	Fair	Good
Distance Estimation	Fair	Good	Good	Fair
Edge detection	Good	Poor	Good	Good
Lane tracking	Good	Poor	Poor	Good
Visibility range	Good	Good	Fair	Fair
poor weather performance	Fair	Good	Fair	Poor
Dark or low illumination performance	Poor	Good	Good	Fair
Ability to communicate with other traffic and infrastructure	Poor	n/a	n/a	n/a

Figure 2: Human vs Driverless Systems (Anon, 2019)

1.1 Literature Review

Formula Student Germany has recently announced that in 2021 there will only be two classes: FSC and FSE (Formulastudent.de, 2019). The driverless event merges with these two. Therefore, all vehicles are supposed to have driverless technology to be able to participate in the acceleration event in 2021 and Skidpad event in 2022. While the other two dynamic events, Autocross and Endurance would still take place with a driver. This essentially means that to still remain competitive whilst being able to compete in all the events Oxford Brookes Racing team has to implement the driverless technology in the upcoming Electric Car before the changes are implemented in the competition in 2021.

The figure created below shows the basic functioning of an Autonomous system and its interaction with Vehicle's Control Unit (VCU). The switch shown below represents the ASMS, which switches 'ON' or 'OFF' the driverless mode.

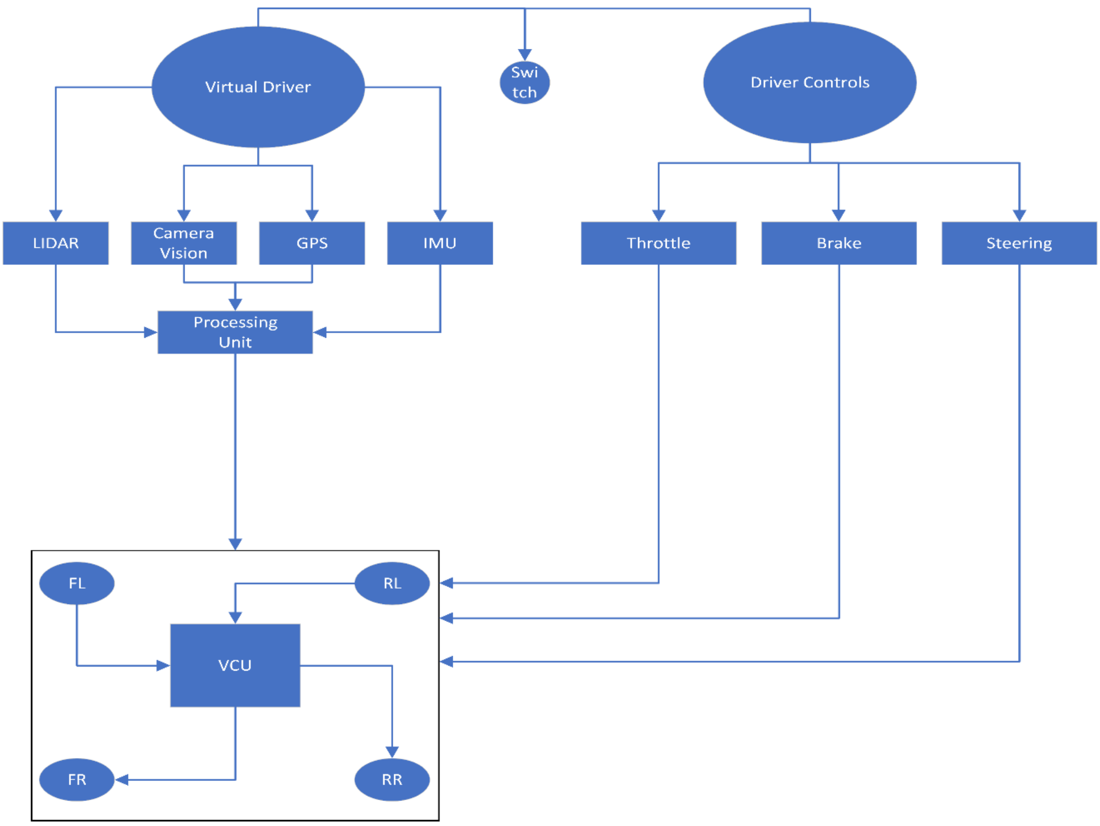


Figure 3: Autonomous System Process

The thesis would provide a detailed analysis of the needs of autonomous car. Various control strategies to implement the straight-line acceleration and Skidpad would be looked into using a

Simulink model tailor-made for this purpose, combined with a simulink based bicycle model (Ni and Hu, 2017). Apart from all the systems the competition requires a remote emergency shutdown system which would help in activating the car in driverless mode (Formulastudent.de, 2019).

The base behind every autonomous action is having a powerful computer (Seilinger et al., 2017). For our needs to convert a regular formula student electric car, a suitable computer which is strong and budget constrained would be proposed. This computer board should able to make decisions based on the sensor readings and should direct the car along the track either with a fixed rule based mapping or real-time track learning. Therefore, it is important that the computer learns the right things using a bunch of sensors, which would be investigated in the course of this thesis. The whole objective of thesis revolves around switching the car from driver mode to driverless mode and hence it is important to have an independent system for the driverless mode (Tian, Ni and Hu, 2017).

The research is based on proposing methods to implement several systems which would work together to make the car driverless. The project would involve study of various subsystems and their integration to convert the current FS Electric car to compete in autonomous mode (Valls et al., 2018). These systems would be analyzed for different strategies using a Simulink model.

The concept of autonomous formula student vehicle is explored in a number of publications, out of which the lack of quality and useful information dilutes the number of publications to one or two good ones. The BIT FSE race car (Ni and Hu, 2017) is converted into the driverless cars and the paper touches upon building the autonomous system, which includes the detection system and path tracking controller. Vehicle modifications, software architecture and vehicle performance in closed loop track testing is briefed upon. Another publication by the same authors (Ni and Hu, 2017) discusses the rules of the competition, which is the most important aspect of race car designing. Their work revolves around creating a longitudinal and lateral controller of the vehicle.

German team TUW racing (Zeilinger and Hauk) has a detailed analysis of the various autonomous events and the design of the autonomous race car. The race car finished seventh in the 2017 edition of the Formula Student Germany competition in the autonomous category. Apart from the design of the race car the paper also focused in the dynamic and static events of FSG. The paper discusses the use of sensors and processing unit of the 2017 autonomous car. However, there is no justification provided on the use of certain sensors. The work defines the software and hardware used in the TUW race car in a very detailed way and provides a good conclusion on the approach of the team.

In the discussion of autonomous FS car, the best team at the moment has provided some of the best publications. All of their work is open source and can be accessed by any one with sufficient interests and knowledge. Most of the work available has been about the description of their respective team's autonomous cars without any justification on the decisions made or about the general functioning of the autonomous race cars. However, this information is clearly useful but at the same time is extremely limited.

The approach adopted in this thesis for building an autonomous race car is to analyze the events in competition and look for ways to maximize the points scored in each event, in this case the acceleration and skidpad events. A framework of autonomous system setup is presented in a logical way with decisions made using appropriate tools for making comparisons and logical reasoning. Cost factor is taken into account and the performance of each component is compared against the requirements.

1.2 Aim and Objectives

There are multiple ways of implementing the driverless technology (Ni and Hu, 2017). A decision matrix between the most appropriate ones would help in deciding the strategy for method implemented. An envelope for the path following controller design would be suggested. This would control the three basic inputs: Throttle, Brakes and steering and would be carried out using Simulink model (Ni and Hu, 2017).

The thesis aims to achieve the following objectives.

- To propose a structure of the sensors' setup including hardware required.
- To investigate and propose a suitable platform (board/Computer) serving as software and hardware integration and propose a method to use it as navigating device.
- To assess different signal based as well as navigation-based strategies and propose an optimal solution for each case.
- To study control strategies of the vehicle by creating a Bicycle model in Simulink, representative of OBR's Electric Vehicle, coupled with modelling of the sensors required for effective running in Skidpad and acceleration Event.
- To implement the control strategy for further verification by creating a Simulink model.

2. Methodology

The motive behind the thesis is to provide a system capable enough, that could be implemented in the upcoming OBR electric car to make it autonomous. There are various challenges in order to accomplish this. The project is broadly divided into two sections, in the first section the sensor setup and actuator setup are decided. In the second section, a suitable control strategy is decided and modelled in Simulink using automated driving system toolbox.

The rules and safety of the competition should not be compromised in any manner and it is important that the systems designed are robust and reliable (Yin, 2018). The various systems that essentially replaces the diver are a set of sensors, a computer to interpret and transmit data for car control. Sensors required would be defined and proposed for the purpose of competing in acceleration and skidpad events. The computer that integrates the sensor data and commands the car via algorithms would also be defined and a suitable one would be proposed. Both the hardware and the software aspects of the board would be defined.

Autonomy in Acceleration and skidpad events has to be achieved compulsorily for the 2021 competition. Acceleration event is basically a straight track of cones, 3m wide and 75m long, with blue cones on the left and yellow cones on the right and orange cones on the start and finish line. A pictorial representation is shown below.

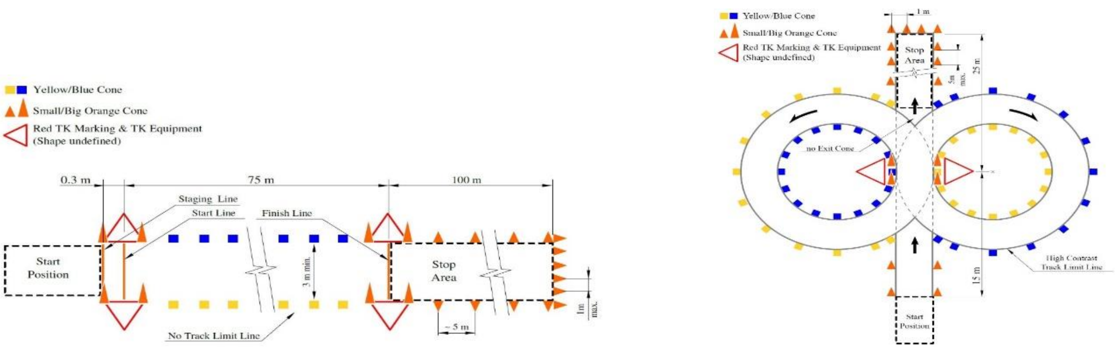


Figure 4: (a) Acceleration Track (b) Skidpad Track (Anon, 2019)

The skidpad track on the other hand is where a very response controller is needed in order to be competitive amongst the top teams. The skidpad track is also 3m wide with blue cones on the left and yellow cone on the right, a representation of the skidpad track is shown below. The dimensions of the track are obtained from the rule book.

2.1 Work Flow and Structure

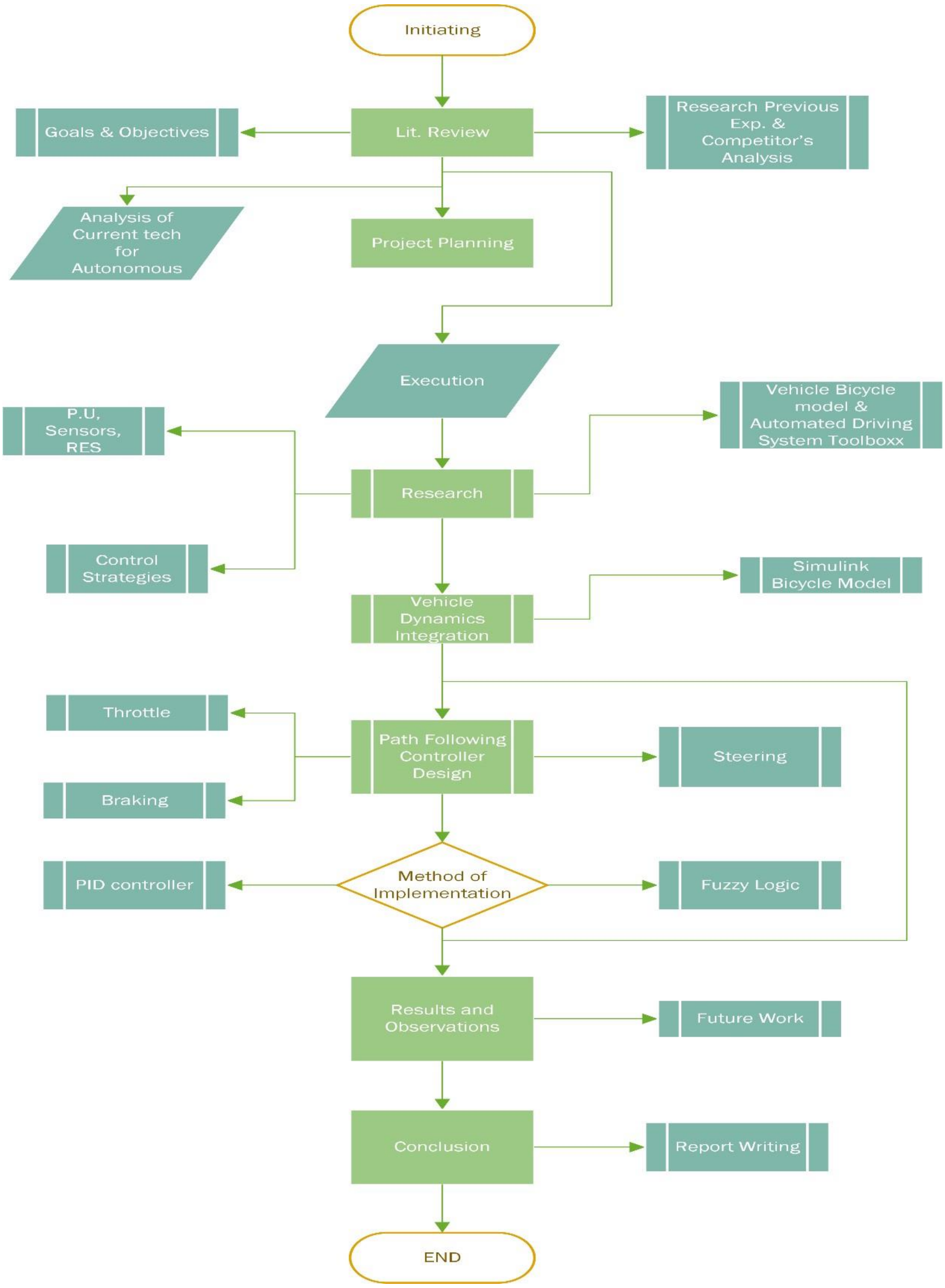


Figure 5: Work Flow and Structure

Area of research for the scope of this thesis has been majorly divided into two sections. An autonomous system consisting of sensor setup and actuators among other rule defines components (RES, ASMS, etc) has been proposed for OBRs FS electric vehicle. The process of selecting each component has been presented and a valuable database has been created based on competitor's analysis and external research.

The second section of the thesis is developing an effective control strategy which could be further developed as the car design evolves. A base model for MPC controller and Lateral Stanley controller has been developed. The MPC controller model has been able to produce better results and could be significantly improved upon. The process of building MPC controller has been presented along with the theory behind its working and tuning of the controller.

2.2 Competitors' Analysis

The analysis would help in verifying the system designed and whether its working to its potential and the dynamics of the car is accounted for. Vehicle's dynamics is a very important aspect as there is a delay between the application of throttle, brake or steering and actual function of throttle, braking or steering. This delay would be accounted for with the help of analytical simulation using Simulink by creating a bicycle model representative of OBR FS Electric Vehicle (Ni and Hu, 2017).

Autonomous cars from Formula Student Germany for 2017 and 2018 is looked with specific details on the autonomous system setup and vehicle specifications. The 2017 edition of the competition saw 15 teams competing in the autonomous category while the 2018 category has seen marginal growth with 18 teams competing.

A list of teams in order of their overall finishing positions for both the 2017 and 2018 edition is presented in tabular format with details of the sensor setups and processing units Formulastudent.de, 2019).

2017 Driverless Teams						
Team Name (Rank Wise)	**Processing Unit**	**Power of PU**	**LIDAR**	**Camera**	**Other Sensors**	**Specialties**
Zurich TU	Robust Master and High-performance Slave	368 GFLOPS	Velodyne Hi-Res	Self-developed inertial stereo camera based on gray-scale FLIR Blackly	SBG Ellipse-N INS, Kistier Correvit SFII Velocity Sensor	Custom Computing and sensor setup, robust against single sensor failure, total weight of the DV system-12Kg
Karlsruhe KIT	Nvidia Drive PX2 and existing Main Control Unit	16000 GFLOPS	2 ibeo LUX, combined opening angle of 160º	1x forward looking 60º angle, 2x side looking with 100º angle	Tightly coupled GPS/INS	fully redundant emergency braking system, self-developed interface to IPG carmaker
Hamburg	LPC 4337, Intel i7-6700K, Nvidia GTX 1070	6573 GFLOPS	2x Ibeo LUX 2010, 4 Layer rotating mirror LIDAR Scanner	1x Basier-acA1300-200uc, industrial high-speed CMOS Camera with Global shutter, USB 3.0	1x Xsens-MTI-G-710-GNSS/INS (IMU)	redundant multisensor perception system, highly adaptive path finding and ideal racing line generation
Stuttgart	Nvidia Drive PX2	8000 GFLOPS	N/A	2 cameras 30m range and 60º, 2 cameras >10m range and 110º angle	N/A	ambitious aims of minimizing lap times and staying within track limits, faster than driver car
Munchen TU	Jetson TX, Vector VN8912, Arduino Due	3656 GFLOPS	50m range, 270º angle, Sick Ims151 2D Laser rangefinder	3 range, 0.1m-infinty/horizon	No Info	Perception system tailored for the FS track, lightweight hardware design simplifying the DV integration onto the car
Hannover	Nvidia Jetson TX1	2000 GFLOPS	Ibeo Lux 2008 4-layer scanner, 50 m range, 110ºx3.2º field of view	2 IDS UI-5240Re-C-HQ PoE Rev2, 30m range, 81.9º CMOS colour global shutter and SXGA	1x inat-M200-SLC IMU (+-450º and +-18G), GPS and RTK	redundant electro-pneumatic emergency brake system, computing unit with gpu and gigabit network

				resolution		
Wien TU	Nvidia Jetson TX2	1500 GFLOPS	1x Hokuyo 30LX	1x ZED stereo Camera	1x Correvit	motion aware perception system
Deggendorf UAS	DATALynx; BeagleBone	4134 GFLOPS	N/A	2x Optitrack Slim 3U	Speed Measurement Unit	High Speed Cameras with 120 Hz, Realtime performance analytics
Munchen UAS	2x Nvidia Jetson TX1, dSPACE MicroAutoBox II	>2000 GFLOPS	No Info	TAMRON MP1010M-VC, 50m Range, mono camera, Stereolabs ZED, 20m range stereo camera	Leica GPS1200+ differential GPS system, Kistier Correvit SFII P	Reinvented path finding among other things. Very cost effective, fulfilling every requirement
Aachen RWTH	Neosys car PC	2064 GFLOPS	N/A	2x StereoLabs ZED camera	IMU, Wheel Speed Sensor, Odometer, RTK GPS	No LIDAR only Camera for perception, Servo motor steering actuation, hydraulic brake actuation
Augsburg	microAutoBox II (IBM PPC 750GL), Embedded PC (intel i7-3517UE, 2x MicroZed Zynq 7020	42 GFLOPS	2x LIDAR 13m Range, infrared short range **RADAR: 1x 70m/250m, 120º/9º, 77GHz Long range**	1x 10m range, 90º, 1080P, 60fps	1x 360º, differential GNSS	” It is simple but fast!”
Darmstadt TU	Nvidia Jetson TX1, Jetson TX2, Intel NUC, NI sb-RIO 9627	1160 GFLOPS	No Info	1x stereolabs ZED 20m range, 110º opening angle stereo camera	Swift Navigation Piksi Multi RTK GNSS Module	Image Processing
Firenze	Nvidia Jetson, MicroAutoBoxII, Custom ECU	156 GFLOPS	No Info	1x CM3-U3-13Y3C	No Info	Kalman Filter, Predictive Control
Ingolstadt	Nvidia Drive PX2	GFLOPS	No Info	2x 60º angle >150m range front facing, 2x	1x dGPS	two rear facing cameras to evaluate driving lane

				100º rear facing		
Beijing	Intel Core i7-6820HK	83.20 GFLOPS	1x Encrader-Zen-1, 360º	1x U3S 1600-H, 60º angle	N/A	servo system for steering and braking, remote operation

2018 Driverless Teams						
Team Name (Rank Wise)	**Processing Unit**	**Power of PU**	**LIDAR**	**Camera**	**Other Sensors**	**Specialities**
Zurich TU	PIP 39, Jetson TX2	3724 GFLOPS	Velodyne Hi-Res	3 cameras, 20 m range, 2 stereo 1 mono layout	INS, Absolute Speed Sensor	Redundant sensor pipeline, robust against single sensor failure, visual LIDAR SLAM Combined, colour independant track identification system
Karlsruhe KIT	Nvidia gtx 1060, intel i7-6700, self designed main control unit	4700 GFLOPS	4 ibeo LUX 2010 (160° opening angle)	3 cameras, Basier Dart, 2 looking forward/sidewards, 1 looking backwards	Xsens IMU MIT G 710, Novatel PwrPak 7D-E1	Redundant camera and LIDAR system, drive locally and also create a map and cal local trajectory, vehicle optimized for camera and LIDAR perception
Hamburg	LPC 4337, Intel i7-6700K, Jetson TX2	6573 GFLOPS	3x Ibeo LUX 2010, 4 Layer rotating mirror LIDAR Scanner	2 x Basier-daA1600-60ucArea Scan with Global shutter, USB 3.0 1600*1200 Pixels	1x Xsens- MTI-G-710-GNSS/INS (IMU), self devpd angle sensor at steering rack	Pneumatic EBS system supplied by compressor directly pressurising hydraulic brake system, near invisibility of DV components on to the electric car ensuring smooth transition
Augsburg	microAutoBox II (IBM PPC 750GL), Embedded PC (intel i7-3517UE, 2x MicroZed Zynq 7020	42 GFLOPS	Velodyne VLP 16 **RADAR: Continental ARS 4xx, Bosch MRRe14HBW**	2x Basier LVDS Camera	Forsberg ReACT GNSS 2x U-Bloxx m8p GNSS	Highly Efficient camera system based on FPGA hardware acceleration, Real time trajectory planning, no blackbox algorithm
Munchen UAS	2x Nvidia Jetson TX2, ETAS ES910	1500 GFLOPS	NO	2 Cameras, 25m range, 76.5º, PYTHON	1xSpeedSensor, 1xAccelerationSensor	self-dvlpd C++ libraries for localization, Single monocular

						camera for envmt detection, customised neural network network for cone detection
Munchen TU	Intel Xeon	756 GFLOPS	Velodyne Ultrapuck	2 colour global shutter cameras with 8mm lens	GPS, IMU	Trajectory Guarantees, Advanced photometric and laser range mapping, agile actuation system
Trondheim NTNU	Nvidia Drive PX2 Auto Chauffeur	16000 GFLOPS	Velodyne Puck VLP-16	2 colour- vision FLIR Blackfly main hoop mounted	Swift Nav Piksi Multi RTK and Vector Nav VN-200 INS	end-2-end machine learning and full driving pipeline. Cone detection combining LIDAR and camera with ML and YOLO3 as redundant system. Earky testing with Gazebo and traxxas RC car
Berlin	Nvidia Jetson TX2	1500 GFLOPS	Velodyne VLP16	Matrix Vision mvBlueFOX3-2	Corrsys Datron SL (2axis), Vectomav IMU VN300 with dual GPS	adaptive Design (30 min to install/remove DV components) one hydraulic system for steering, clutch and brake
Aachen RWTH	Nvidia Jetson TX2	2072 GFLOPS	2x SICK LD-MRS420201, 110º angle, 300m range	2x ZED Cameras, 20 m range, 110º angle	Sensonor STIM300 IMU	Redundant object detection via stereo camera and LIDAR, full onboard localization with optional GPS
Weingarten UAS	Nvidia Drive PX2 Autochauffeur	N/A	Velodyne VLP-16	1x Intel RealSense D435	N/A	Sensor fusion using ROS between Camera and LIDAR
Goteborg	AMD Ryzen 7	42	Velodyne Puck	stereolabs ZED	SBG Ellipse-2N INS	combines LIDAR

Chalmers	1700, Beaglebone Back STM32	GFLOPS	VLP-16	camera		and Camera. Steering control by Velocity dependant aimpoint considering no of cones and velocity
Hannover	Simtrones ABOX-5000G1	2000 GFLOPS	2x Ibeo Lux 2010 4-layer scanner, 50 m range, 85º angle	2x Baumer - VLG-20CI-1/1.8	1x inat-M200-SLC IMU (+-450º and +-18G), GPS and RTK	redundant electro-pneumatic emergency brake system, computing unit with gpu and gigabit network
Dresden TU	Teensy 3.2 MicroAutoBox with Embedded PC	345.6 GFLOPS	Velodyne Puck Hi Res	N/A	N/A	N/A
Darmstadt TU	Nvidia Drive PX2, dSPACE MicroAutoBox II	9600 GFLOPS	Velodyne VLP-16 Hi Res	Autonomous Smart Stereo Camera, 110º opening angle	VectorNav VN-300, Kistier Correvit SFII	Sensor Fusion of LIDAR and Camera localization by differential GPS, pneumatic brake actuation
Budapest	Nvidia Jetson TX2, TMS570LS1227	1500 GFLOPS	Velodyne VLP-16	Basier acA2040-120uc mono camera, stereoiabs ZED stereo camera	VectorNav VN-300	nothing special
Kempten UAS	Texas Instruments TDA2x, Atmel 90CAN128	6.33 GFLOPS	N/A	GigE, uEye, FA, ½" OnSemi Python, 1300CMOS Farb sensor, 1280x1024 pixels, Global Shutter, Trigger-E	Peak System PCAN GPS, Programmable Sensor Module, satellite receiver, magnetic field sensor, accelerometer, gyroscope, CAN	simple and effective, building a robust system was the aim
Ilmenau TU	Nvidia Jetson TX2, dSPACE MocroAutoBox II, Intel NUC7 i7, STM32 Board	1600 GFLOPS	Velodyne VLP-16	1x Stereolabs ZED stereocamera, 110º opening angle	VectorNav VN-300 INS	sensor fusion of camera and LIDAR
Stuttgart**	Xilinx Zynq 7000, Nvidia GTX1070, i5-7500T, x86 PC	6000 GFLOPS	Velodyne VLP-16	2x Cameras 60º, 2x cameras 100º	IMU, Optical Speed Sensor	ambitious aims of minimizing lap times and staying within track limits, faster than

						driver car

A similar method is followed to create a database of autonomous system setup for the teams in FSG 2018 has been created. The database contains a few of the same teams from ’17 which had completely changed their approach after just one year. This change has been predominantly because of how new this concept is and unlike the more established traditional formula student competition, teams have no idea and knowledge of how to proceed. Therefore, it is important to have a directive of what is the right path to go on when making the decisions.

The 2018 system setup list also adds new components, meaning the expansion of market for autonomous components. The list of teams with different sensor setup according to their finishing position is shown below.

The project is divided mainly in to two sections. In the first section a sensor setup is proposed for OBRs FS electric car. The setup consists of sensors, steering actuators and rule book derived components like RES and ASMS. Different sensor setups, drawn from the database created above, are compared.

In the second section, a suitable control strategy is decided and proposed. MPC and Stanley controllers have been studied and modelled in Simulink. MPC controller has the proven record in the competition with majority of driverless teams using the MPCC controller. Stanley controller was designed by a team competing in DARPA challenge for their autonomous SUV.

2.3 Autonomous System Comparison for OBR FS

Once the teams were analyzed, it was important to understand the different design philosophy that each team have adopted and to figure out which one could be most suitable for the OBR Electric Autonomous car. In order to achieve the desired result with credibility, a decision matrix system was adopted wherein each of the components were allocated scores based on various parameters and features.

One of the key functions of a driverless car is object detection. This is done through vision sensors like Camera and Lidar. The LiDAR provides up to 0.2mm accuracy in cone detection. This is essential in making sure that no cone is hit due to inaccuracy or non-detected cones. The camera helps in creating a visual aid that can also add depth to the cones and provide a wide-angle detection. The other two sensors needed for making the car autonomous are GPS/INS and IMU. The localization of the car on the track at any instance on a certain point is done by using the GPS. IMU helps in determining the slip angle and yaw among other dynamic properties of the vehicle.

Processing unit is the computer on-board, which processes the data from all the sensors and helps in running the software for mapping, localization and path planning. The sensors communicate via CAN to the computer on-board, which sends the suitable signal of throttle, brake or steering to the VCU.

Processing Unit						
	NVIDIA Jetson TX2	**NVIDIA gtx 1060**	**Nvidia Drive PX2**	**NVIDIA gtx 1070**	**Sintrones abox - 5000**	**In-Car PC**
Processor	256 Core Pascal	1280 Core architecture Intel i7, 3.2 GHz	2560 core Pascal Architecture	Intel i7, 3.2 GHz	Intel i3/i5/i7/Xeon	Customizable
RAM	4GB/8GB DDR4	6GB DDR5	16GB DDR4	6GB DDR5	Up to 32GB	Up to 32GB
Memory	32GB eMMC 5.1	SSD external req	128GB eMMC 5.1	SSD external req	32GB	SSD as per request
Performance	1 TeraFlops	N/A	8 TF & 16 TF	N/A	N/A	N/A
Features	On-board WiFi, Sufficient for FS Purpose, cheaper than PX2	High Performance Gaming Solution Board, Cheaper than gtx 1070	Best amongst the competitors by a large margin. Very Powerful, but expensive	High Performance gaming solution board	Fanless, Offers wide variety of options with the components, Inbuilt GPS Unit	Fanless, Highly Customizable according to the needs, Inbuilt GPS Unit
Weight	3-6 Kgs					
Cost	800£	500£	£6,000	500£	1800£ (Appx)	2,500£

Figure 6: Processing Unit Technical Comparison

A database of LiDAR is created and the most suitable ones based on common logic and cost is compared and is shown in the table below. The table below shows the technical specifications of commonly used LiDARs.

LIDAR				
	RoboSense RS-LIDAR-16	**Velodyne VLP-16 Puck**	**Ibeo LUX 4L/8L**	**SICK LD MRS 420**
Range	0.2m - 150m	100m	0.5m-150m	0.5m- 150m
No. of Channels	16 Beams	16 Channels	-	-
Vertical FOV	30º (+-15º)	30º (+-15º)	3.2º	3.2º
Vertical Angular Resolution	2.0º	2.0º	0.8º	0.8º
Horizontal FOV	360º	360º	110º	110º
Rotation Rate	5Hz- 20Hz	5Hz- 20Hz	-	-

Wavelength	905 nm	903 nm	905nm	905nm
Working Voltage Range	9-32V	9-18V	9-27V	9-27V
Accuracy	+-3cm	+-3cm	+-10cm	+-10cm
Weight	0.84 Kg	1Kg	1Kg	1Kg
Cost	2,500£	6,350£	8,000£-16,000£	2,775£- 7,130£

Figure 7: LiDAR Technical Comparison

The cameras have been compared in a similar manner as shown above. Camera is the vision of the car and is an important aspect of the autonomous system. Camera can eliminate the need for LiDAR and other similar sensors. Tesla has already progressed in to Autonomous cars without LiDAR or Radar, using only Cameras.

Zed Camera Stereo Labs has been chosen as the most suitable one as it provides depth detection, which is a useful feature for object (cone) detection and would have more prominence moving forward to the no LiDAR era.

Camera					
	Basler daA1600-60ucAre	**Basler LVDS**	**FLIR Blackfly**	**Zed Camera ROS-StereoLabs**	**Baumer**
	CMOS sensor 1.2Mp-5Mp PYLON Upto 60fps	Frequencies from 20-84 MHs CMOS sensor 24 data bits per clock cycle BCON software	Global Shutter CMOS sensor Myriad II VPU 0.4-12.3Mp Options available	Dual 4Mp camera High Frame rate, 1080p HD video @ 30fps 110º opening angle	Upto 20Mp CMOS sensor Global and Rolling Shutter
Cost	100£	100£	200£	350£	220£

Figure 8: Camera Technical Comparison

Another critical set of sensors for an autonomous system is the IMU and GPS module. GPS helps in localization of the car and IMU takes vehicle’s dynamics in to account for interaction with the software. The imu and GPS module are shown below. Peak PCAN Gps and IMU module has been selected for the ease of installation and accuracy. It is also worth noting that the Peak PCAN module is cheapest option available.

IMU and GPS/GNSS/INS/RTK							
	XSens MTi-G-710 GNSS	**Forsberg ReACT**	**Swift Nav Piksi Multi RTK**	**Vector Nav VN-200/300**	**Sensonor STIM 300**	**SBG Ellipse - 2N INS**	**Peak PCAN GPS and IMU**
	10º/h Gyro Bias Stability Dynamic Roll/Pitch of 0.3º and Yaw of 0.8º Input V: 9-24VDC	Dynamic Roll/Pitch of 0.2º RTK (Real-Time Kinematic) Input V: 9-36VDC	1.08º/h Gyro bias Stability Dynamic Roll/Pitch of 0.5º Input V:5-15VDC Needs MEMSENSE IMU along	0.3º Dynamic Heading Dynamic Roll/Pitch of 0.1º Extremely Light Weight	10º/h Gyro Bias Stability Input V: 4.5-5.5 VDC	Dynamic Roll/Pitch of 0.1º Input V:9-36VDC	+- 16 G of Accelerometer measuring Range Micro SD Card Slot Input V: 8-30VDC
Price	3400£	N/A	480£ + 900£	2100£	7000£ (appx)	8000£ (appx)	220£

Figure 9: IMU/GPS/GNSS Comparison

The most important component of the autonomous system is the processing unit or the computer on-board (Anon, 2019). Every team has a different approach in selecting the board and this is also governed by the budget allocated for the processing unit. Various processing units commonly used by the teams and some more based on the suitability have been compared against one another.

Computer Selection								
Criteria	Weighting	Nvidia Jetson TX2	Nvidia GTX 1060	Nvidia Drive PX2	Nvidia GTX 1070	Sintrones ABOX 5000	In-Car PC	COMMENTS/NOTE
Processor	1	3	4	5	4	5	5	chipset used
Performance	3	3	3	5	2	3	3	overall performance offered by the computer in terms of response rate, etc
Cost	5	3	5	1	5	4	3	
Weight	4	3	3	3	3	3	3	
Additional Features	3	3	0	3	0	3	5	In-built components, services offered, etc
Performance offered versus performance required	3	4	2	1	2	3	4	Ahighl6y powerful computer can do the job,but is it really required for our objective
	Total	60	56	49	53	64	68	

Figure 10: Processing Unit Decision Matrix

The matrix shows that the processing unit best suited for our needs is the customizable In-car PC unit. The computer could be tailor-made according to our specifications and the various components would be assembled together. In-Car PC allows the user to build a computer with custom features. The customizable features of the pc include, RAM, processor, memory, etc. While the drawback of in-car pc is it is air cooled unlike the Nvidia (Anon, 2019) which offers liquid cooling, which also adds weight. Autonomous tech society at Oxford Brookes University has tested the cooling of in-car pc with a small CPU fan, barely adding any weight or electronic load and has observed that the fan is sufficient to keep the computer cool.

LiDAR is one of the major components and can be very useful. The above LiDARs are all within the price range and are suitable to do the job, however to

choose one among the four models a decision matrix is drawn and is shown below. Each feature is weighed according to importance and the models are marked as per the performance

Lidar Selection					
Criteria	Weighting	Robosense RS-LiDAR-16	Velodyne VLP-16 Puck	Ibeo LUX 4L/8L	Sick LD-MRS-420
Range	3	3	3	3	3
Vertical FOV	1	4	4	1	1
Vertical Angular Resolution	1	5	5	2	2
Cost	5	5	3	1	3
Weight	2	4	3	3	3
Horizontal FOV	4	5	5	2	2
Accuracy as Claimed	4	4	4	2	2
Reliability and Make	3	2	4	5	4
	Total	93	87	54	61

Figure 11: LiDAR Technical Comparison

in that department relative to each other.

Sixteen channeled Robosense LiDAR is selected based on its credibility on-paper. It has similar architecture as of the Velodyne, but is much cheaper. The accuracy claimed by Robosense is better than the Velodyne Lidar, this can only be verified once the comparisons has been drawn between the two on similar working standards.

2.3.1 Steering and Braking Modifications

Steering is a complex factor in converting the FS electric car in to an autonomous vehicle. FS teams, previously have tried and tested several iterations of the steering system.

One of the major design constraints in a FS car comes in the medium of Rule book. The first place to begin the design of brake and Steering was to assess the rule book thoroughly. A series of videos published by the Formula student Germany, where different teams share their experience and failures particularly on steering and braking, was very useful in finalizing the autonomous steering and braking system.

To design an effective steering system, some of the sensors are mandatorily required. They are torque sensor, Steering angle sensor and a data logger. It is also important to conduct experiments on the predictability of the torque. The simplest of tests would be to conduct a static test with a torque wrench. These sensors are commonly used by the formula student teams even though they do not have driverless systems. The tests to determine accurate steering torque required are also commonly performed by the teams at the top level. All this is used by the team to improve the vehicle dynamics of the car and can be used for the autonomous systems as well.

The most common power steering system used by the industry in normal road cars is hydraulic steering system. Hydraulic steering, however has several complexities when tried to be designed in to a race car like Formula students. The hydraulic system is also tremendously heavy for a small racing car, this also prevents the designer from achieving the required weight distribution, among other challenges of increased weight. Therefore, the hydraulic steering system was not considered as a viable option.

Several designs were drawn out and all concepts were listed down for its pros and cons. Every design concept was different and unique. Actuation of steering column from the top, actuation of rack linearly, actuation of steering column from the edge of the pinion gears were some of the actuation points and the best four designs have been shown below.

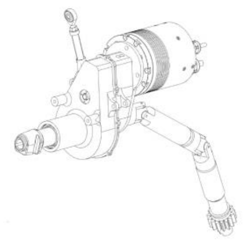
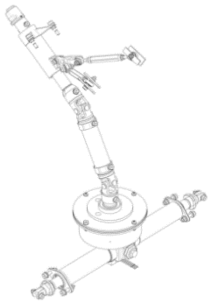
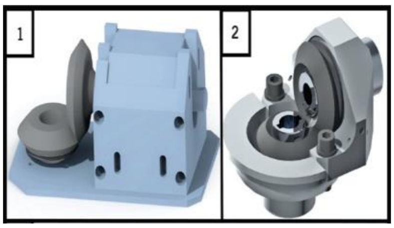
Steering Design Concept Type		Advantages	Disadvantages
	**DC Brushless Motor with Gear Box**	• Smaller motor required, resulting in less current consumption and lesser load on the accumulators	• The setup would require more space in the tightly packed cockpit. • Weight of the system would be higher • Driver require more effort to turn the steering wheel because of hindrance from the gearbox
	**Linear Actuator**	• Occupies less space inside the cockpit • Integrated with the rack	• Weight distribution problem for the car • Integration with the car leading to stronger suspension linkages • Driver require more effort to turn the steering wheel because of hindrance from the gearbox • High RPM motor required for quick actuation
	**Direct Drive System**	• Occupies less space inside the cockpit • Hollow motor glued the steering column • No gearbox required, hence less weight • No additional torque required by the driver to turn the wheel	• System requires major modification to the steering system • High torque motor required, leading to increased current consumption and load on accumulators
	**Bevel Gear system with Brushless Motor**	• Occupies less space inside the cockpit • Small brushless DC motor used, resulting in less current consumption • Bevel gear setup used, reducing the driver hindrance to steer	• Custom made gearbox and gear box casing required to effectively utilize the system • Driver effort to turn the steering still higher than direct drive system

Figure 12: Steering System Design Concepts Comparison

The direct drive hollow shaft motored steering seems to be the best option in terms of packaging and offers the desired steering through the parallel gearbox. The advantage with this design is the drivability remains as easy as before. The motor offers close to zero resistance in the steering of the car. On the other side, however the motor requires lot of time with to function as per the commands due to encoding issues. Therefore, it is important that the encoder selected is in terms with the motor and the manufacturer is contacted right from the beginning.

Another approach to providing sufficient steering torque without consuming much electric current is by innovative thinking and simplifying the design of gear box to use bevel gears instead of helical gear with a conventional DC motor. This provides a more rigid support to the motor on the cockpit and space constraint is also eliminated. A suitable solution to steering design concepts is provided in the result section.

Brakes are another important aspect of the autonomous car. Each year, the organizers of FS Germany publish a new guide on how to design the Braking system for an autonomous car. Designing the EBS is has to be in tandem with the braking system designed for the car. As per FSG rule book article T5.1.4, a driverless car can have brake-by-wire system, however when in driver mode the brake by wire system is prohibited and cannot be used.

There are two option on the braking system

- To create a separate brake by wire system for the autonomous mode, which is practically not feasible
- The second option is to create an assembly for the hydraulic cylinder to be actuated autonomously with the help of an actuator system or stepper motor system.

The rule book states particulars on how to develop the brakes and when the brakes should be actuated which is also presented in the appendix on the instruction manual.

2.3.2 Steering motor and encoder

Steering motor required for this purpose depends upon the design being used for the autonomous steering. It is important to consider factors that affect the application of steering motor on to the column. The car has to be driven around by the driver with the steering motor in place, this requires extra effort from the driver in case of geared or belt driven arrangement. A direct drive motor setup, will provide close to no resistance. The motor has to be glued in as near to the pinion gear for accurate operation. The TQ Robodrive RD50*08-HD hollow shaft motor with 15Nm peak torque can be used to actuate the steering.

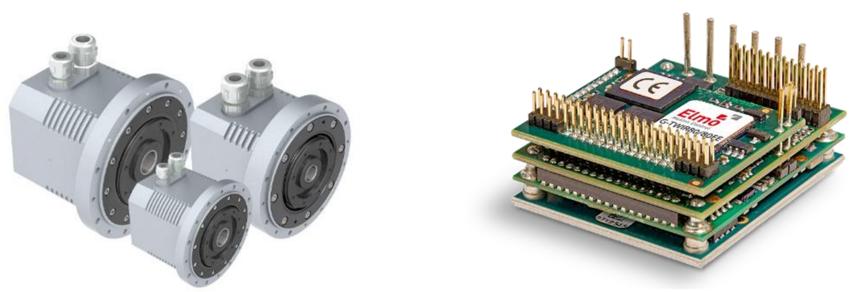


Figure 13: Steering Motor and Encoder

Encoder is required to supply closed loop feedback signals based on speed and position of the motor shaft. Elmo motion control creates encoders which have proven track record in the industry with some of the leading industrial manufacturer using encoders form Elmo motion control. It provides wide range of working voltages from 8-60VDC. The gold twitter Elmo motion encoder also supplies continuous power output ranging from 800-2000W depending on the supply.

The other aspect of the thesis is to propose a suitable control strategy. The autonomous system components are analyzed thoroughly and a suitable solution to each component is proposed in the result section. The steering of an autonomous car is done using a controller designed in using software. There are numerous controller techniques available to choose from and each of them has pros and cons. In the section below control mechanisms are discussed.

2.7 Simulation

Two control strategies have been studied, MPC and lateral Stanley. The controllers have been modelled separately in Simulink. A bicycle model is created which is representative of OBRs FS Electric vehicle. The bicycle model was initially created in ADAMs multi simulation software and later recreated in Simulink.

MPC controller has been prioritized because of the advantage it provides over Stanley controller in terms of speed and accuracy. The main advantage of MPC over PID and other controllers is that it keeps optimizing the current time space, while also keeping the future time spaces in memory. MPC controllers predict the change in dependent variables in the plant model (bicycle model) that will be caused by changes in independent variables. These independent variables which could not be controlled by the MPC are input as disturbance separately as an improvement to the base model.

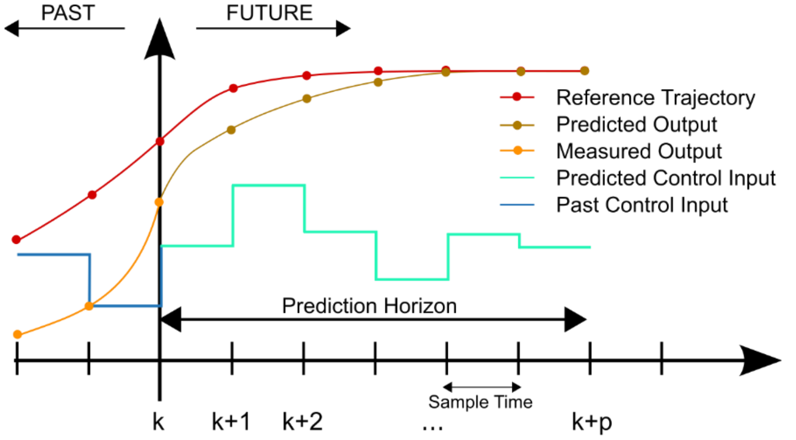


Figure 14: Theory behind MPC Control

The MPC calculates the error in the independent variable and the changes are implemented for the current time space only. The calculations are repeated for the next changes for each of the time space. The controller used is a linear MPC controller, as the system can be assumed to be linear over a short operating range. Use of linear MPC also allows for improvement with each calculation due to the feedback mechanism.

2.7.1 Vehicle Bicycle Model

Once the setup is completed, a control strategy suitable for skidpad and acceleration events is analyzed in Simulink. A bicycle model representative of the FS electric vehicle is modelled. Initially it was decided that the bicycle model would be created in ADAMs as it provides more complexities that could be added to the model in lesser time. The bicycle model created in ADAMs is shown in the image below.

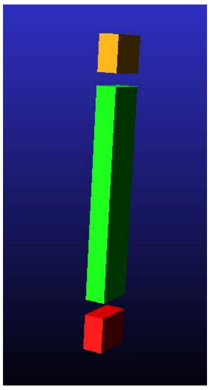


Figure 16: Adams Bicycle Model

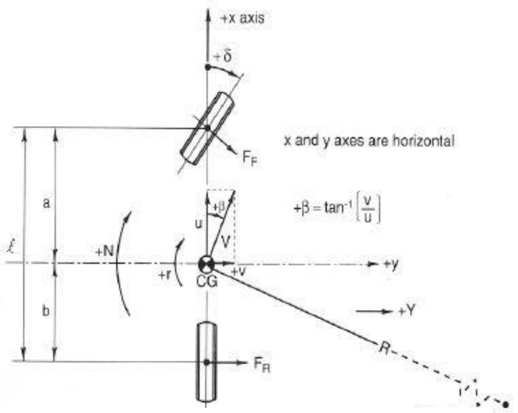


Figure 15: Theory behind Bicycle Model

The model created in ADAMs had the capabilities of following the path. The model was also capable of taking wheel slip and yaw angles in to consideration. The model also had the pacejka's tire model taken in to consideration. The model lacked aerodynamic loads at the time and was supposed to be improved upon.

However, the sensors had to be modelled in Simulink and linking the ADAMs bicycle model with the Simulink automated driving toolbox was found to be slow. The bicycle model had to be simplified in order to run the models simultaneously. Therefore, a similar bicycle model was created in Simulink. The details of which are presented below.

The model is based on the following equations

$x' = V.Cos(phi + beta)$

$y' = V.Sin(phi + beta)$

$phi' = V/lr.Sin(beta)$

$V' = a$

$Beta = Atan[(lr/(lf + lr)).tan(delta)]$

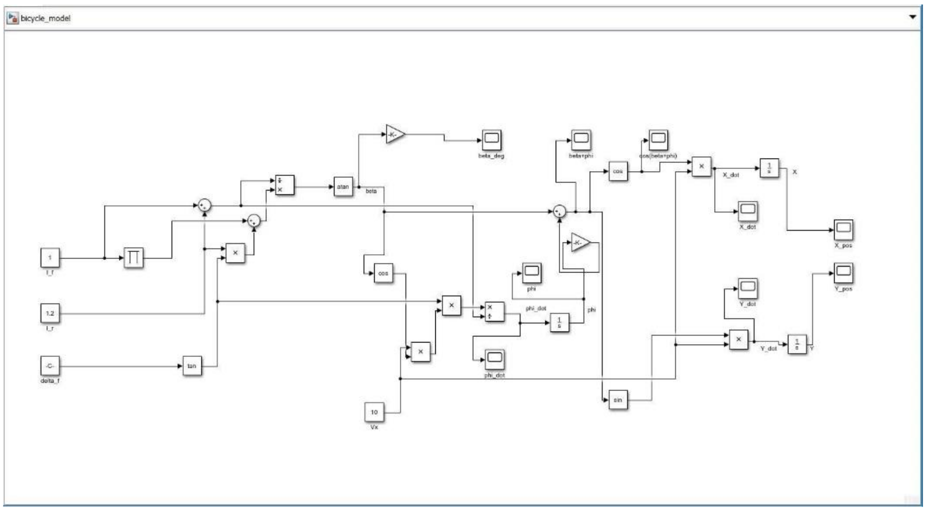


Figure 18: 2 DoF Bicycle Model

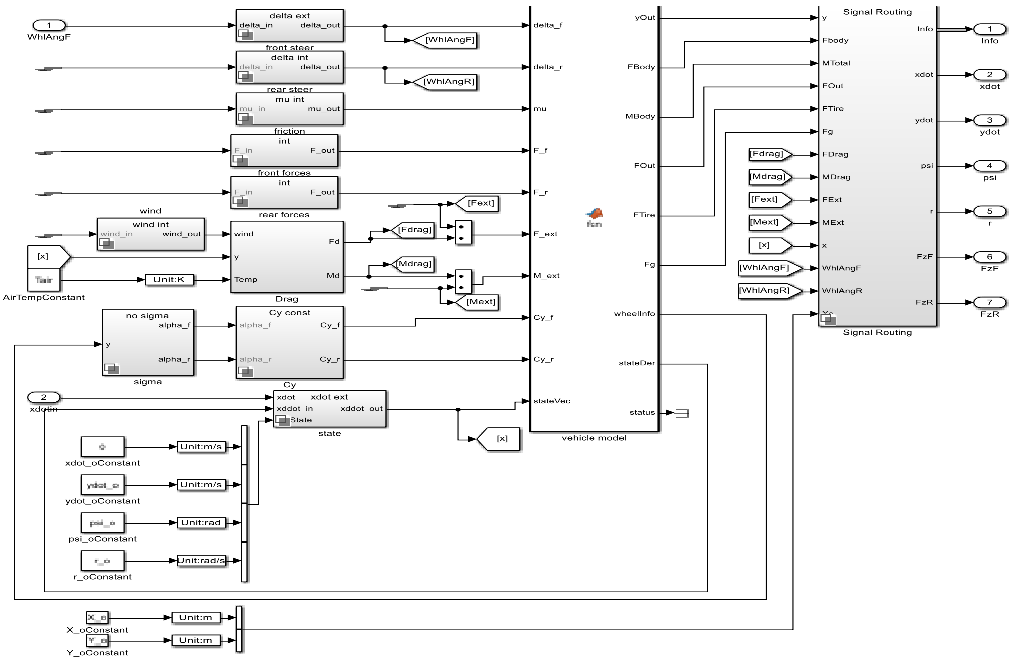


Figure 17: 3 DoF Extended Bicycle Model

The bicycle model is then improved to represent a 3 DoF model with Yaw, Longitudinal parameters and one that can take tire slip effect and inertia in to account. The 2DoF model was improved to 3 Dof model. The model can account for Yaw, Longitudinal and normal forces, tire slippage. This is then used as feedback input for the MPC controller. The model is then masked in order to obtain a cleaner workspace. The masked bicycle model can be adjusted with a dialogue box and the parameters that can be edited are shown below.

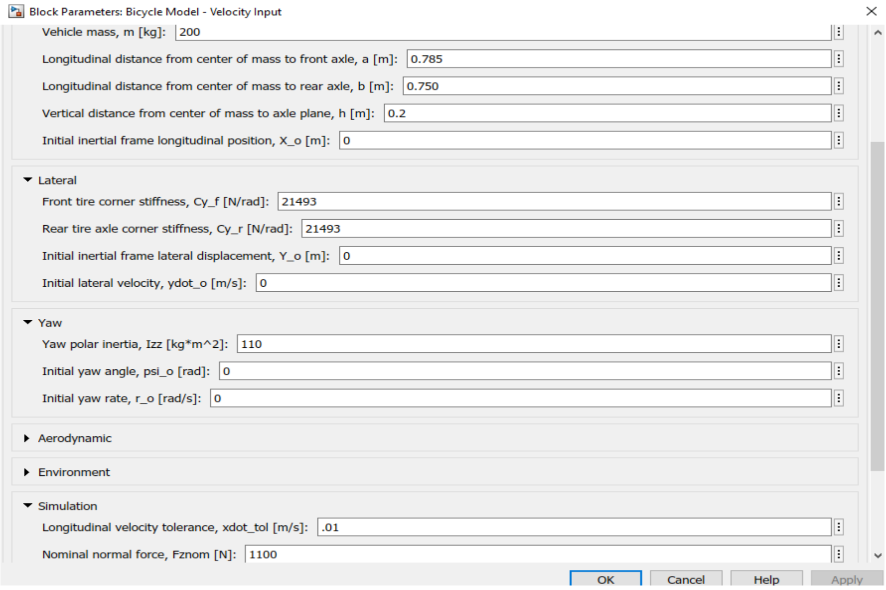


Figure 19: Variable Parameters of 3DoF Model

2.7.2 Track and Ego Vehicle Designer

The simulation is input with waypoints of the vehicle on the track and road coordinates obtained from the rule book of Formula student. This is generated using the Driving Design Scenario Application of the Matlab.

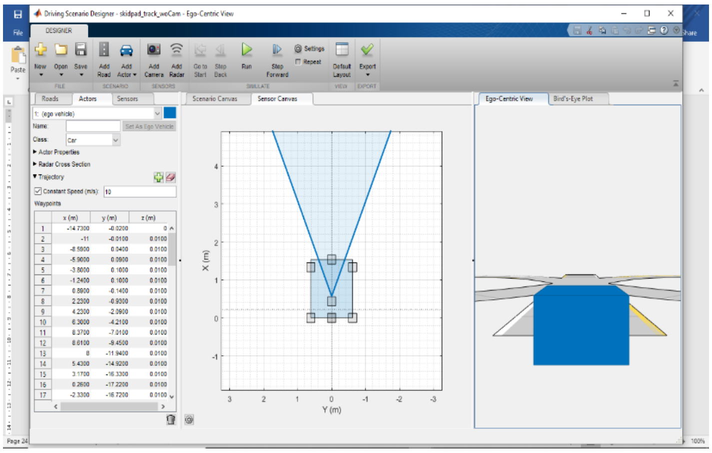


Figure 21: Actor and Track Characterization in Driving Scenario

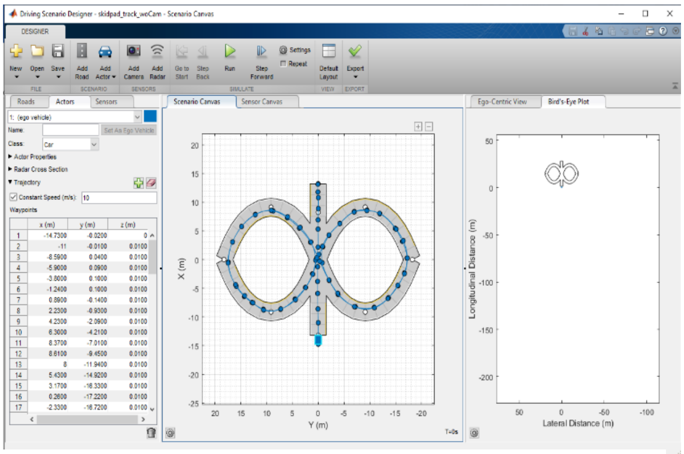


Figure 20: Camera Addition to the actor model

The track, Ego Vehicle and the Camera vision are then exported as matlab function, which is used for bus creation of vehicle's waypoints and lane boundaries. This is used as an input to the MPC controller among other parameters.

2.7.3 MPC Controller

The MPC controller block from 'Automated driving toolbox' is used. The block requires Yaw angles and track reference points as inputs and outputs calculated steering angle. Controller takes error calculated from the difference between the actual position of the front axle of the car to the reference position obtained from the Driving scenario. The error is minimized for each current step, while the future steps are also kept in the memory.

The tuned controller can be then used to obtain a quick simulation of the system. The controller is then exported to Simulink. The response plots, thus being a quick and effective way to evaluate each parameter in closed loop response. The simulation length and variety of types of setpoints (impulse, ramp, step, etc.) over the controller variable can be set based on the requirements.

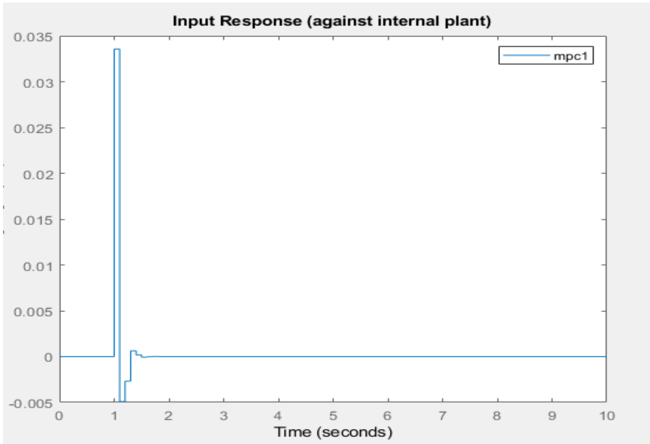


Figure 23: Controller Result for MV

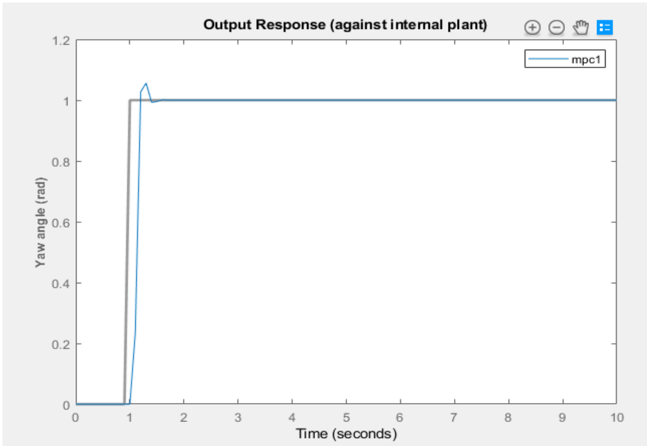


Figure 22: Controller Result for CV

The controller is tuned for the set variables and the pre results are plotted in the above figure shown. There are two plots, one for the Manipulated Variable (MV) and one for Controlled Variable (CV). These plots are represented as input response and output response respectively. The model is presented below.

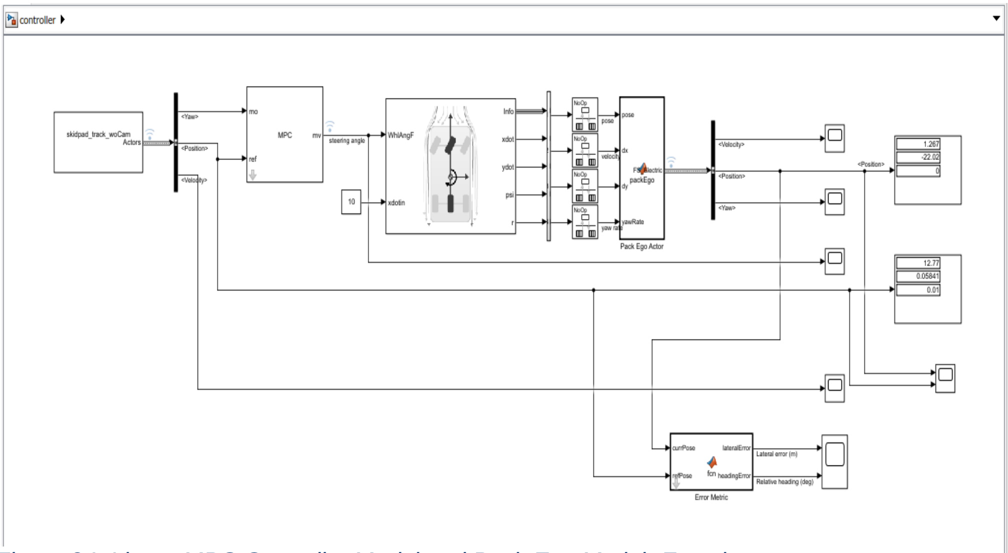


Figure 24: Linear MPC Controller Model and Pack Ego Matlab Function

Several parameters required as feedback input for the vehicle have to obtained by further processing of the simulation. To obtain these parameters a matlab function is created. Matlab codes for these Matlab Function blocks can be found in the appendix and the block is highlighted in the image below.

A lateral Stanley controller was also modelled in the Simulink. This model had been discussed in detail in the section below.

2.7.4 Lateral Stanley Controller

Stanley controller was first developed by 'Team Stanley' in the DARPA challenge, where a real-world SUV is driven around autonomously on an off-road track. It is generally used for calculating steering command for a path following model. This would particularly useful for our purpose if the mapping is highly accurate.

An extended workspace was required for the creation of inputs. Automated Driving system toolbox of matlab 2019a has a pre-loaded standard block for Stanley controller which combined with the plant and the supporting models could produce effective results. Two types of Stanley controllers are used in the model shown below, a kinematic model and a dynamic model. The user can switch between the two for comparisons.

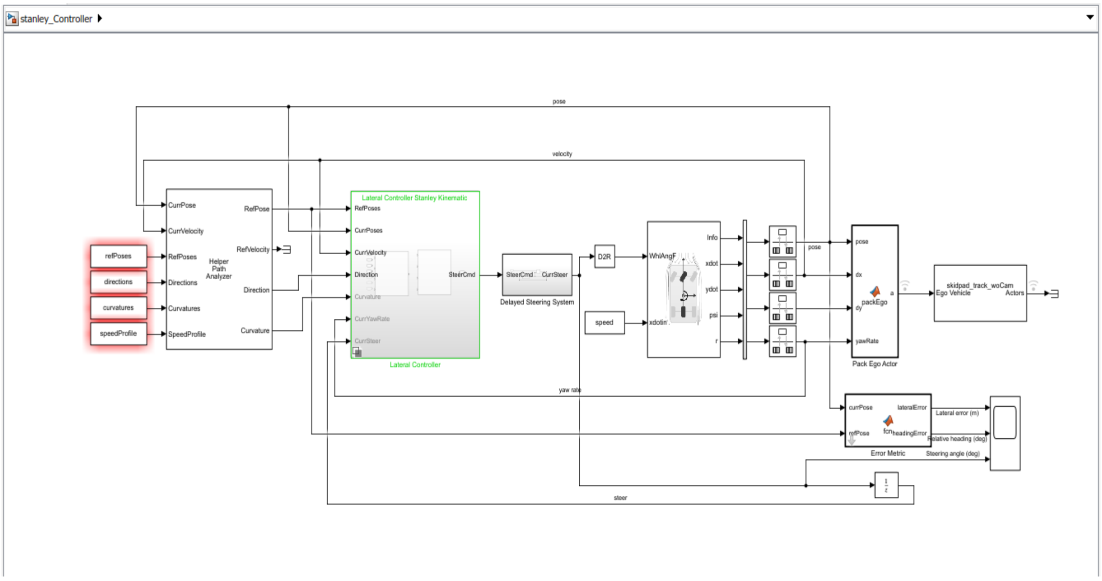


Figure 25: Stanley Controller Simulink Model

A base model is created for the purpose of understanding the theory and functionality of the lateral Stanley controller. The model does not produce credible results which could be used to compare with MPC controller modelled above.

The MPC controller modelled has its limitations. The model can have independent variable input as disturbance for the model. The system is assumed to be linear over a short operating range. The linear MPC controller modelled for the simulation can be further improved to non-linear adaptive MPC controller.

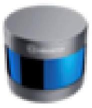
3. Results and Discussion

The thesis is divided in two parts as shown in methodology, proposal of autonomous system (hardware) and developing an effective control strategy. An overview of how to convert the FS car to autonomous is drawn and presented in the appendix section.

The project requires research in autonomous vehicles and competitor's analysis. It is very important in Formula Student competition to stay ahead of the competitors in whatever way possible. It is also desired to achieve the results with minimum budget as that creates further impact on the static events of 'cost' and 'design'. A detailed analysis of the autonomous system setup is conducted and presented. Points based decision matrix system is used to select each component and the price amongst various other specifications have been listed. A database of system setup is created, which could be looked upon in the future and improvised decisions could be made with progression in time and changes in price. A setup of sensors and Processing Unit (PU) is selected after extensive study and using common logic and points-based scoring system a decision is made on the sensors' and PU's selection.

3.1 Hardware System Setup

Final Sensor setup for the driverless car is presented below.

	**Processing Unit: In-car PC** • intel core i7 • External SSD compatibility • Fan less, Air cooled
	**LiDAR: Robosense RS-LiDAR-16** • 16 channels • 0.2-150m range • +-3cm accuracy
	**Camera: Zed camera by stereolabs** • Wide angle • Depth detection sensor • 30 fps, 110º opening angle
	**GNSS: Peak PCAN GNSS** • Robust and reliable • Cost effective
	**Steering motor: TQ Robo drive RD50*08** • Hollow shaft, 15 Nm peak torque • Brushless DCC motor
	**Remote Emergency System (RES): Gross Funk GF2000i, t53 receiver** • Compulsory as per rules for the competition

A guideline of how the electric FS vehicle can be converted to Autonomous vehicle is represented in Appendix.

3.1.1 RES and ASMS

It is mandatory for every driverless car to have a Remote Emergency System and ASMS (Autonomous System Master Switch). Formula Student Germany also specifies on the model of RES to be used.

Gross Funk manufactures and supplies remote controls for Cranes and heavy-duty construction vehicles. The receiver to be used in the competition is Gross funk's gf 2000i-codec and the transmitter combination to be used is gross funk's T53R98. Receiver has to be supplied with 12-24V and consumes approx. 0.26a current at 12V. The shutdown circuit designed for the EV has to have Normally Open (NO) relays which is also on the receiver. Emergency stop button on the RES must trigger the Shutdown Circuit.

ASMS is also mandatory for the driverless vehicles. The master switch acts as the actuation point for steering, braking and throttle. When the ASMS is 'Off' the actuation should not happen even upon the request of the autonomous system. However, the sensors and the processing unit can stay operational for gathering of data. Steering actuation cannot happen even when the ASMS is 'ON'. For the steering actuator to be operational, autonomous state has to change to "Ready to Drive". The steering can stay active during emergency brake maneuver.

3.2 Simulation Results

Vehicle's yaw parameters and the steering inputs required are being able to be studied using the model. The lateral position of the car with respect to vehicle coordinates can also be studied. The bicycle model is created as such to provide as many information as possible. This is done in order to extract more parameters in the future.

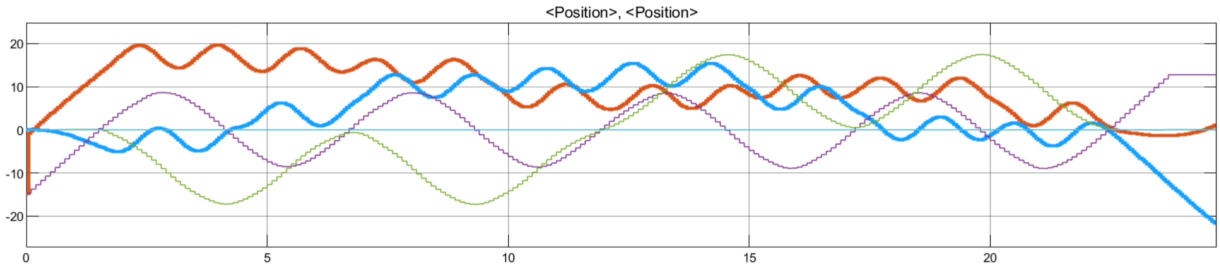


Figure 26: Actual Position of the Car compared to the Driving Line Car Should Follow (10mps)

The above graph displays the difference in actual positions and the current positions in X and Y coordinates of the vehicle when travelling at 10mps constant velocity. Simulation takes 24.7 seconds to complete. There is a disturbance and lag of less than a second which is due to the limits of controller tuning options available in the current model. The model can be improved by adding the new adaptive MPC controller block with more input and output parameters. The lag observed in above plot represents responsiveness of the controller.

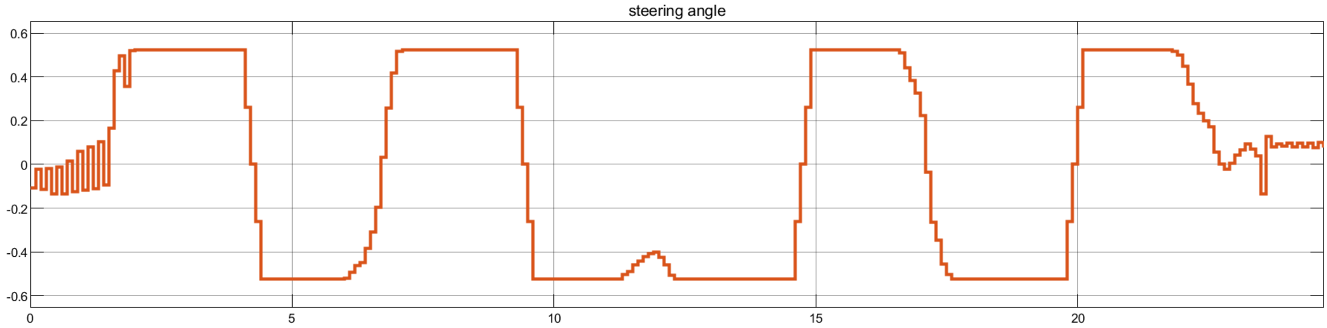


Figure 27: Steering Angle (in rad) at 10mps

The plot shown above represents the steering angle required to complete the skidpad track. This is obtained using the virtual simulation designed in driving scenario and is the input parameter for bicycle model. Y-axis shows the angle of the steering required to complete the corner in radians, while X-axis shows time. The results obtained are at 10mps velocity constant velocity of the vehicle.

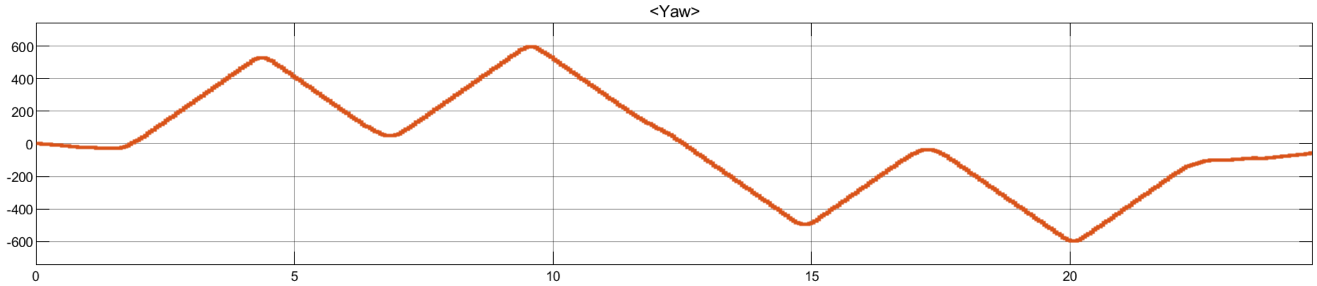


Figure 28: Yaw Angle of the car at 10mps

Yaw characteristics of the car can be studied in the above shown graph, the graph could be smoother and less peaky with improvement in the tuning of the controller and with addition of new parameters for the controller to predict steering angle. Peak yaw angle of 11 degrees is achieved by the car at the exit of the turns.

MPC controller model generated here is dependent on the Mapping. The car has to map the track first in order for the controller to takeover. However, in case of Mapping failure, the vehicle still needs to be quick. A look ahead feature needs to be modelled in to the current setup in that case. For the scope of this project a great baseline is set, which could be worked upon for further improvements.

Same three parameters are measured with the constant velocity increased to 15 mps and are shown below. The simulation takes around 15 seconds to finish.

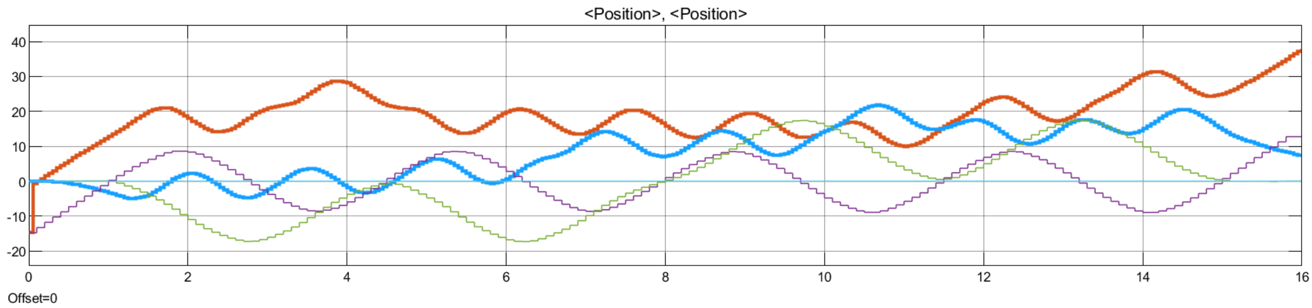


Figure 29: Actual Position of the Car compared to the Driving Line Car Should Follow (10mps)

The controller has also been tuned accordingly to reduce the error, it is believed that further tuning is possible. The error between and actual position is now reduced to less than half a second as can be seen from the plot above. Car goes a bit wayward at the first entry to the right circle. The controller however, quickly takes control within a second. The responsiveness of the controller has been improved in this iteration as well as the vehicle velocity.

The steering angle required is again full lock, as the maximum steering angle is locked as per the design of the steering system of the EV car. Therefore, the plot for steering angle vs time is similar to the one above. Noise disturbance observed at higher speeds is also higher as can be seen during the straights at the start and finish.

4 Conclusion

Formula student is an intense and grueling competition if the car is not designed up to standards. However, teams that do well on the track has taken right decisions most of the time during the design phase. Most affordable sensor setup while also being the most suitable for our purpose has been proposed in the thesis.

While in a road car which has to encounter a tougher scenario needs to have vision on all the sides covering as much ground as possible. In case of Formula Student, there is no particular scenario where vision of the rear of the car is required. A partial side vision can also be used to achieve similar results as that of full side vision. The camera also has depth detection capabilities which would be helpful in future when the software is developed enough to eliminate other object detection sensors like Lidars, etc.

An educated and sensible decision-making technique is adopted, in an attempt to make the right decisions. A table of database is created, which summarizes the sensor setups used by different teams in formula student Germany. This database is then further used to evaluate the pros and cons of each setups and decision matrices are drawn for each sensor and actuator. RES and ASMS has been discussed in detail in accordance with the rule book and implementation with the shutdown circuit.

Steering the driverless car is a challenging task. Car should be drivable by the driver with the steering actuator in place. A geared motor to actuate steering increases the turning torque required by the driver to turn the wheels, while also adding weight and occupying space in a space constraint area of the car. A direct drive system with a high torque motor glued to the steering shaft is the most suitable option in terms of steering torque, weight and space. However, a high torque motor applies more load on the accumulators.

A suitable control strategy has been proposed and modeled in simulink. Two controllers have been modelled, MPC and Lateral Stanley controller. A bicycle model has also been developed which is representative of the OBR FS Electric car. This bicycle model is used as plant for the controller model and further results of the vehicle has been predicted. This controller can be further improved by tuning and adding noise and disturbance parameters. The Stanley controller model has been created but the model is not working properly.

The sensor setup proposed in the thesis creates a roadmap for the autonomous formula student car. The setup doesn't necessarily satisfy every Formula student driverless car, but the methodology used is the best way to reach a conclusion. This work has not been done by any other team or author before. The controller design comparison attempt made in the thesis provides a direction. Every team uses different steering strategies and every year changes to different control strategy. This is due to the uncertainty present with the autonomous cars. The issue is addressed in the thesis with great detail. Several teams in Formula Student are currently clueless on how to convert their car to autonomous vehicle. This thesis will help in providing a step-by-step guidance on how to convert their current car to driverless vehicle while also helping in identifying key hardware components required.

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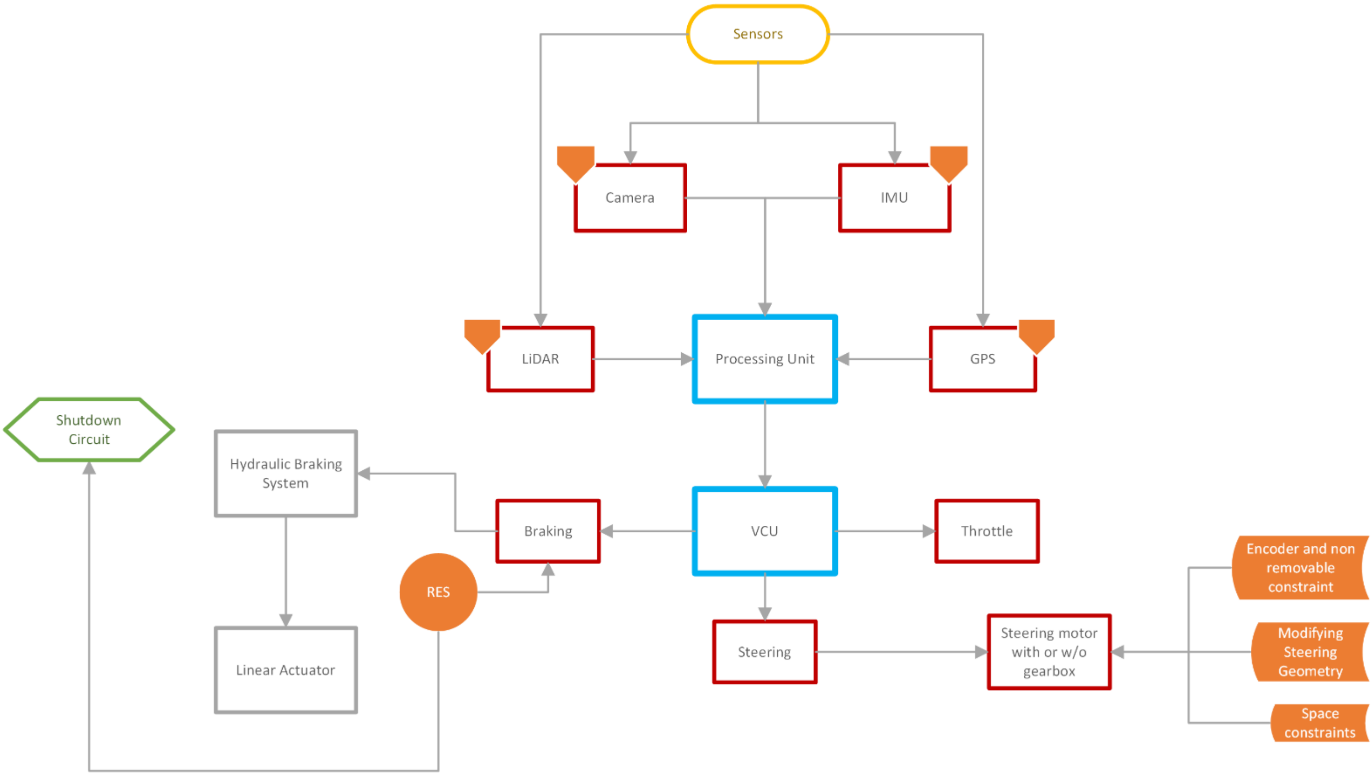
7 Appendix

Appendix A: Conversion and Component Specifications



LiDAR	Camera	IMU/GPS	Processing Unit	Steering Motor	RES
Robosense RS-16	ZED stereo Camera	Peak PCAN GPS and IMU	In-Car PC	TQ Robodrive RD50*08-HD	Gross Funk GF2000i series

The basic requirements of Autonomous vehicle have been discussed in detail in the thesis. This section provides certain instruction necessary for the conversion of the electric vehicle to driverless car.

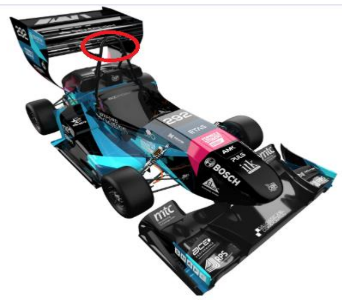
Processing Unit secured safely on the c-cabin or driver cockpit, depending on whether data collection needs to be done and computer on- board is kept ON when driven around by driver

Processing Unit (Computer): In- Car PC					
Processor	RAM	Memory	Weight	Cooling	Cost
Intel i7	32 gb	External SSD	5 kg (approx.)	Air Cooled, No fan	2500 GBP

- Lidar positioning is inspired by its position on the IMechE's car. Lidar to be mounted securely at the center of front wing without obstruction.

LiDAR: Robosense RS-16										
Range	No. of Channels	Vertical Angle of Resolution	Vertical FoV	Horizontal FoV	Rotation Rate	Wavelength	Working Voltage range	Accuracy	Weight	Cost
0.2-150 m	16	2.0º	30º (+-15º)	360º	5Hz-20Hz	905 nm	9-32 V	+-3 cm	0.84 kg	2500 GBP

- Camera Position is not inspired by its position on the IMechE's car. Camera is to be mounted at the top of the car at the roll hoop height.



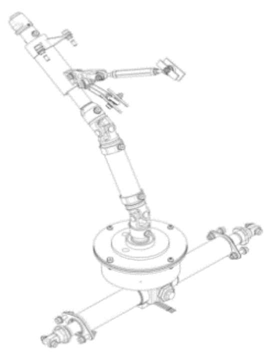
Camera: ZED Stereo Camera				
110 º opening Angle	4MP Dual Camera	Wide Angle, Depth Detection	1080p HD video @ 30 fps	350 GBP

- IMU securely mounted inside the c-cabin.
- GPS module mounted on the A-cabin on top

GPS and IMU: Peak PCAN GPS			
Input V: 8-30VDC	Micro SD card Slot	Bosch Accelerometer and magnetic field sensor	Accelerometer measuring range +-16G

- RES module transmitter and receiver has to be installed. The antenna has to be mounted obstruction free on the top of roll hoop.

- Steering motor glued in on the steering column near the pinion.



Steering Motor: TQ Robodrive RD 50*08-HD						
Power	Nominal Torque Output	Peak Torque Output	Output Speed	Gear Translation	Nominal Voltage	Nominal Current
210 W	7.8 Nm	28 Nm	55 n_{max}	1:100	48 V	5.1 A

Appendix B: Pack Ego Actor Script

```
function FS_Electric = packEgo(pose,dx,dy,yawRate)
% Pack ego information into a single ego actor bus
%
% Imoprtant note:
% Output is a bus of type BusActorsActors. This is the same bus used by the
% Scenario Reader to output an individual actor. If you change the
% output bus name of Scenario Reader, change the output bus name here
% as well by clicking on 'Edit Data' in the menu above.

FS_Electric = struct(...
    'ActorID',1,...
    'Position', [pose(1) pose(2) 0], ...
    'Velocity', [dx dy 0], ...
    'Roll', 0, ...
    'Pitch', 0, ...
    'Yaw', pose(3), ...
    'AngularVelocity', [0 0 yawRate]);
```

Appendix C: Driving Design Scenario Script

```
function [scenario, egoVehicle] = skidpad_track_woCam()
% createDrivingScenario Returns the drivingScenario defined in the Designer

% Generated by MATLAB(R) 9.6 and Automated Driving Toolbox 2.0.
% Generated on: 09-Aug-2019 13:29:26

% Construct a drivingScenario object.
scenario = drivingScenario;

% Add all road segments
roadCenters = [0 0 0;
    9.125 -9.125 0;
    0 -18.25 0];
roadWidth = 3;
road(scenario, roadCenters, roadWidth);

roadCenters = [0 0.1 0;
    -9.125 -9.5 0;
    0 -18.25 0];
roadWidth = 3;
road(scenario, roadCenters, roadWidth);

roadCenters = [0 0 0;
    9.125 9.2 0;
    0 18.25 0];
roadWidth = 3;
road(scenario, roadCenters, roadWidth);

roadCenters = [0 18.25 0;
    -9.2 9.125 0;
    0 0 0];
roadWidth = 3;
road(scenario, roadCenters, roadWidth);
```

```
roadCenters = [0 0 0;
    13.2 0 0];
roadWidth = 3;
road(scenario, roadCenters, roadWidth);

roadCenters = [0 0 0;
    -13.2 0 0];
roadWidth = 3;
road(scenario, roadCenters, roadWidth);

roadCenters = [5 15.5 0;
    -0.7 17.8 0;
    -4.2 16.1 0];
roadWidth = 3;
road(scenario, roadCenters, roadWidth);

roadCenters = [5.06 -15.46 0;
    -0.37 -17.86 0;
    -5.05 -15.59 0];
roadWidth = 3;
road(scenario, roadCenters, roadWidth);

% Add the ego vehicle
egoVehicle = vehicle(scenario, ...
    'ClassID', 1, ...
    'Length', 1.535, ...
    'Width', 1.23, ...
    'Height', 0.8, ...
    'Position', [-14.73 -0.02 0], ...
    'FrontOverhang', 0.2, ...
    'RearOverhang', 0);
waypoints = [-14.73 -0.02 0; -11 -0.01 0.01; -8.59 0.04 0.01; -5.9 0.09 0.01;
-3.8 0.1 0.01; -1.24 0.1 0.01; 0.89 -0.14 0.01; 2.23 -0.93 0.01; 4.23 -2.09
0.01; 6.3 -4.21 0.01; 8.37 -7.01 0.01; 8.61 -9.45 0.01; 8 -11.94 0.01; 5.43 -
14.92 0.01; 3.17 -16.33 0.01; 0.26 -17.22 0.01; -2.33 -16.72 0.01; -4.55 -
15.49 0.01; -6.65 -13.64 0.01; -8.32 -10.86 0.01; -8.2 -7.21 0.01; -6.06 -
3.86 0.01; -3.63 -2.15 0.01; -0.54 -0.79 0.01; 2.3 -0.85 0.01; 4.28 -2.09
0.01; 6.26 -4.19 0.01; 8.29 -6.97 0.01; 8.54 -9.44 0.01; 8.05 -11.91 0.01;
5.31 -15.11 0.01; 3.29 -16.51 0.01; 0.26 -17.28 0.01; -2.45 -16.72 0.01; -
4.49 -15.43 0.01; -6.78 -13.51 0.01; -8.38 -10.92 0.01; -8.2 -7.03 0.01; -
5.87 -3.8 0.01; -3.56 -2.09 0.01; -0.29 -0.3 0.01; 3.04 1.49 0.01; 5.49 3.66
0.01; 7.28 5.98 0.01; 8.47 8.72 0.01; 7.87 12.17 0.01; 5.76 14.84 0.01; 3.07
16.59 0.01; -0.46 17.4 0.01; -4.66 15.86 0.01; -6.41 14.33 0.01; -7.47 12.82
0.01; -8.66 10.62 0.01; -8.66 7.29 0.01; -6.88 4.49 0.01; -4.86 2.47 0.01; -
2.48 1.1 0.01; -0.1 0.51 0.01; 3.05 1.4 0.01; 5.61 3.48 0.01; 7.45 5.92 0.01;
8.58 9.07 0.01; 7.81 12.17 0.01; 5.76 14.84 0.01; 3.07 16.59 0.01; -0.58
17.46 0.01; -4.37 16 0.01; -6.29 14.25 0.01; -7.53 12.64 0.01; -8.78 10.56
0.01; -8.6 7.23 0.01; -7 4.38 0.01; -4.86 2.41 0.01; -2.54 1.04 0.01; 0.32
0.27 0.01; 2.16 0.03 0.01; 5.31 0.03 0.01; 6.92 0.03 0.01; 8.88 -0.03 0.01;
10.79 -0.03 0.01; 11.78 0.05 0.01; 13.13 0.05 0.01];
speed = 10;
trajectory(egoVehicle, waypoints, speed);
```

Appendix D: RES Quotation from Gross Funk

Gross Funk® radio remote + automation

Mobile Radio Emergency Stop „Formula Student“

Type GF2000i/T53R98/02743, order number. 100-016-617

Transmitter T53 for 12 V battery

- increased transmission power for larger ranges
- stable and robust design
- hard-wearing aluminum cast housing
- protection class IP65

Receiver serie GF2000i R98 Codec

- plastic housing, DIN rail assembly
- power supply: 12/24 V/DC
- 1 emergency stop-output potential-free
- clamps for direct wiring
- protection class IP20

Delivery scope
Transmitter, receiver, bag, 2 batteries 12 V, 1300 mAh
Automatically charger 230 V AC, receiver miniflex antenna

(For further details see enclosed technical information)

Total price: € 1788,00 plus VAT and shipping

Gross-Funk GmbH
Wiesenstraße 6
D-67707 Schopp

Tel.:+49 (0)6307/9212-0
Fax.:+49(0)6307/6609
www.grossfunk.de

christian.keller@grossfunk.de
Tel.: +49 (0)6307/9212-27

Additional 50Euros is charged for delivery