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Driverless for Racecar Implementations

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Autonomous cars are becoming a part of daily lives and changing the automobile. With this improvements autonomy is making its way to motorsports.
With this in mind Formula Student opened a new type of competition for Driverless Vehicles in 2016. Due to very few teams competing in Driverless Competitions and to be more relevant to the student's studies Formula Student Germany (FSG), the governing body of all Formula Student events, decided to make Driverless capability a requirement to compete starting from 2021. Over this decision many teams scrambled to start their development of driverless.
This paper aims to provide necessary help to such teams and those who would like to develop driverless a starting point while also acting as a road map for the teams who wish to develop driverless but have no access from their respective universities. The goal is to provide an informative paper about driverless, how to develop it and where to get help when developing.
In this paper various resources are introduced, discussed and evaluated for the developer. Also, important points to remember while developing, developing methods, basic infrastructure of a driverless system are also discussed.

Keywords	Driverless, Autonomous Vehicles, Formula Student

Contents

List of Abbreviations

RADAR	Radio Detection And Ranging. Utilises radio waves to detect objects
LIDAR	Light Detection And Ranging. Utilises light to detect objects.
SONAR	Sound Navigation And Ranging
FOV	Field Of View. The zone which sensor can detect.
NFOV	Narrow Field Of View.
WFOV	Wide Field Of View.
SAE	Society of Automotive Engineers.
NHTSA	National Highway Traffic Safety Administration.

1 Introduction

1.1 Motivation

Developing driverless car for new students is complex subject there is a lot of information about driverless but very few on to develop it. These few resources all their own understanding and method. This work provides a new developer information on how to start developing and how to proceed. In this paper developer could also find helpful tips to consider when developing a driverless race car. It should be considered that while this work focuses on driverless segment on Formula Student all developers who wish to develop performance based driverless car can use this work to start.

1.1.1 Open Field for Advancement

Driverless is a very new subject that is entering our daily lives, this results in the field being open to advancements. Considering the latest achievements made by computers motorsports offers new unknowns and variables in to the game.

1.1.2 Ability to Integrate New Ideas

Driverless cars allow for new ideas to be tested, new concepts to be formed and new boundaries to be determined on roads. So far, all the theories on integrating driverless have been scrapped or cancelled so there is very little precedent on how this integration will take effect.

1.1.3 Learning Experience

Learning to develop driverless requires knowledge on software engineering, computer engineering, hardware design, sensor, image processing, machine learning, vehicle dynamics, and many more fields for better performance. So, a developer for driverless cars needs to learn a lot of information when developing resulting in a very nutritious learning experience.

1.2 What are Driverless Cars

Driverless cars are autonomous vehicles which operate without a driver or an operator. Driverless cars recently got attention from the industry with the advancements in its most limiting factor, computing. With the latest developments computing power that fits in a van in 1980's now fits in to battery size computers. This development allows for more hands-off experience in autonomous vehicles whose capabilities are also used in driverless vehicles.

1.2.1 Difference between Driver Operated and Driverless Cars

A driver operated car requires or may require a driver or an operator to operate properly, in driverless cars such operator does not exist so the car has to act autonomously. A driverless car may be operated by a driver depending on the design.

1.2.2 Difficulties of Driverless Cars

Driverless cars suffer from the same difficulties as the autonomous vehicles. Although autonomous vehicles usually have drivers to support them driverless vehicles solely rely on their system and if anything goes wrong and supervisor structure is insufficient vehicle may involve in an accident. So driverless vehicles are more demanding than autonomous vehicles.

1.2.3 Current Implementation

Currently almost all driverless efforts go to road car development for civilian use. There are very few bodies that try to turn this into the sport These bodies are Formula Student and Roborace. Roborace is FIA supported official race for driverless vehicles while Formula Student is an amateur league for students to enhance their skills.

1.3 What is Formula Student

Formula Student is a series of events where students from various universities compete in designing, creating and building a small formula car. These event's main purpose is

for students to learn and gain experiences in their own fields also learn from some other fields. These events are focused on development in automotive industry.

1.3.1 General Information

In 1980 Formula Student was formed for students who are interested in automotive to learn and experience difficulties in auto industry and to learn more for their crafts. Managed by Institution of Mechanical Engineers and Society of Automotive Engineers. Formula Student rules change each year to promote redesign, rebuild of a new car each year, also to create new challenges.

1.3.2 Formula Student Rules of 2021

Formula Student Rules state that in 2021 all formulas which participate in the events needs to have driverless capabilities. This work provides resources and insides on how to develop and aspects to consider while developing.

1.3.3 Existing Driverless Teams

There are 59 Registered Driverless teams in Formula Student. And on average data gathered on 27 of these teams it takes 15 Master's Degree students one year to develop driverless. So, universities without the robotics master's degree are expected to develop driverless in a longer time.

2 Related Work

2.1 Driverless for Formula Student Cars

Driverless for formula cars and racing cars in general is a new concept. The material available is fairly limited. So, the team which produces most materials and can go into detail will be winning the races.

2.1.1 Problem Definition

Since we are making the driverless model from road car systems, we need to adjust the road conditions to racing conditions.

2.1.1.1 Road Conditions

First that comes to mind when thinking about road conditions is the complexity of the warnings all around, other cars horns, traffic lights, pedestrian crossings, bicycles, other cars, congested traffic and the list goes on.

2.1.1.1.1 Everyday Usage

We have to remember that that we are racing on specific days and conditions. So, we don’t need to think about everyday operation such as daily commutes, short cuts, avoiding traffic, fuel level, oil level, winter tires vs summer tires, air condition…

- **Behaviour towards other drivers.** Racing is all about winning. In order to win, cars need to be aggressive. This results in bumper to bumper racing at high speeds, much closer than road car rules and crashing is very possible. A driverless car needs to weigh in the situation, and attempt overtake of defense maneuvers accordingly.
- **Single car lanes.** There is no actual “lane” but the full track shared by all the cars, which is a bit chaotic for the driverless system. But when racing lines are considered as lanes it becomes a bit simple to understand for the system.
- **Traffic lights.** Apart from racing control lights and flag there are no stop signs and traffic lights, and race control already provides necessary information about race condition to the cars directly removing the need for light reading and flag reading software reducing load on the system.

2.1.1.1.2 Comfort Based

Road cars prioritize comfort and safety over speed. So, a necessary adjustment to the software making the cars more performance based is necessary.

- **Pushing car.** In racing, the cars are pushed to their limits that determines who wins and who loses. In road cars such behaviour is non-existent. So, the developer for the driverless must “teach” the car to push the limit while keeping in control.
- **Engine.** A relaxed working engine is a long-lasting engine, but in racing we don’t need high mileage. We are looking for performance.
- **G-Forces.** In road conditions acceleration is very slow, in race conditions faster acceleration and faster deceleration is applied. Not just the longitudinal G-forces are higher lateral forces are high as well.
- **Wide turns.** We mentioned road conditions being based on comfort, by making turns wider, lateral accelerations are reduced providing a more comfortable drive. In race track tighter the turns better the results. It should not be forgotten that compromising tightness of the turn vs speed when taken the turn should be considered while programming turn controllers

2.1.1.1.3 Speed Limits

There are very few speed restrictions on track compared to the roads, and these speed restrictions are usually already embedded to the car physically like engine limitations, restrictor plates for internal combustion engines and power limit on electric motors.
Conservative Rules
There are much more rules in road cars which are stricter while in racing rules are often bent for better performance as long as these bends are within toleration, also it should be taken in to account what penalties exist for each rule braking and how much risk will be taken should be carefully thought.

2.2 Education for Driverless

Due to its complexity developing driverless requires good education and good skills. There are a couple of ways to gather the information required for developing driverless. For related work two of these ways are taken in to account and further investigated. The methods investigated is Master’s Degree Studies, which provide diploma, and Online courses, which provide certificate.

2.2.1 Master's Studies

Driverless Cars are named as Autonomous Vehicles in the literature, thus all the available courses in the Universities are named after Autonomy. Autonomy and robotics courses can be found in many universities but for this example two universities are picked.

ETH Zurich (AMZ Racing)

ETH Zurich, home university of AMZ Racing team, offers the most competitive Driverless team in Formula Student. This university has a dedicated degree program and a research lab for robotics which is usually associated with driverless cars. This lab serves as a starting point in Autonomous cars, students learn basics of autonomy and produce their own project at the end of the year. It should be considered that this lab produces city like scape and small carts for it, once students learn how to develop autonomous vehicles, they can proceed to develop Driverless Formulas. This proves that integration on studies effects the performance of the teams greatly.

University of Toronto

University of Toronto (UofT) has a different standing in the world of Autonomous Vehicles., this can be seen by their collaboration with Coursera and creating a nanodegree programme in Autonomous Vehicles. Although being very advanced, UofT does not have an active Formula Student team.

2.2.2 Online Courses

Other than Master's Degree programmes most students can be educated through online courses. At the time of writing this thesis, there are four main courses which the developer can take. In the later review of the education material two of these courses, Coursera and Udacity, are discussed.

Coursera

As it is stated before Coursera teamed up with UofT to create this nanodegree program. This program is more academic oriented with fine details and offers deep understanding.

Udacity

Udacity teamed up with industry to provide more industry-oriented program. It provides faster implementation but developer is limited in terms of understanding deeper concepts.

Udemy

Udemy also offers Autonomous courses although much more limited compared to their industry or university backed counterparts.

MIT

MIT offers a limited course for autonomous driving focusing on only machine learning aspect of autonomy.

2.3 Standards in Driverless

Just like any other subject driverless cars are subject to regulations which follow standards set by main authorities. Driverless cars have had strict regulations and standards since they first revealed to the end customer.

2.3.1 Industry Standards

Industry standards are made up of road cars, so in addition to the standard regulations applied to the road cars there are more regulations and standards set for Driverless cars. One of the most important authorities in this area is Society of Automotive Engineers (SAE) International.

SAE Levels

SAE divided the Autonomy into six levels and set standards to this industry. All the automotive authorities around the world agreed to set SAE standards into their regulations. With their report they not only standardized autonomy levels, but also set how the vehicle should act on certain scenarios. This reports purpose is:

1. Clarifying the role of the (human) driver, if any, during driving automation system engagement.
2. Answering questions of scope when it comes to developing laws, policies, regulations, and standards.

3. Providing a useful framework for driving automation specifications and technical requirements.

4. Providing clarity and stability in communications on the topic of driving automation, as well as a useful short-hand that saves considerable time and effort.

(Copied from SAE, Ref. 1)

Level	Name	Narrative definition	DDT		DDT fallback	ODD
			Sustained lateral and longitudinal vehicle motion control	*OEDR*		
Driver* performs part or all of the *DDT						
0	No Driving Automation	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	Driver Assistance	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	Partial Driving Automation	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
***ADS* ("*System*") performs the entire *DDT* (while engaged)**						
3	Conditional Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	High Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	Full Driving Automation	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

Figure 1: Driverless levels stated by SAE and used as standard (Surface Vehicle Recommended Practice, SAE, 2018)

2.3.2 Race Standards

The standards set in the road cars don't always apply to races, but with no authority present in Driverless races and no unison in how the Driverless races will be conducted

there is no real concrete rules or regulations. Even the only entity that can be considered as an authority Roborace changed their minds from 2017 to 2018 significantly changing the concept.

2.3.2.1 Formula Student Standards

So far, the only motorsport body with more concrete rules is Formula Student which is regulated by Formula Student Germany. Each year new standards are set and strictly regulated and starting from 2016.

2.4 Sensors

All driverless cars have sensors on. Since their commercialization sensors became the defining feature of driverless cars and these two aspects go hand in hand.

2.4.1 Why Sensors are Needed

For the driverless car to interact with the world around it, it needs to sense the world around it. For this an array of sensors are used. Each sensor's weakness and advantage are discussed in another section

2.4.2 Available Sensors

- **Cameras:**
  Cameras have been around for very long time but the digital cameras are around since 1975. Introduction of digital cameras allowed machines to see the world as humans did and brought the ability to interact with it. Early cameras had very low resolution but it was enough to perceive the image taken but computers were not as advanced to process images. This was the main reason why development of driverless was postponed.
- **Light Detection And Ranging (LIDAR):**
  LIDARs were developed during the 1960s, same time as the invention of lasers, as cloud measuring devices. First notable use of LIDARs is the Apollo 15 mission where it was used as an altimeter. LIDARs have developed very much since their single dot measuring days, now Lidars provide 3D images at almost the same vertical resolution as the first cameras. Their use in driverless vehicles was so common the it became the main feature to detect if a vehicle is Autonomous.

- **RADAR:**
  First use of radars in cars was around 1980s with Toyota for early collision warning. Other manufacturers followed suit, and radars became more common in cars and used in many different applications.
- **SONAR:**
  SONAR is used as paring sensor in cars. First used in 1970s for aiding the blind but developed into parking sensors in 2000s with Toyota. Sonars gained popularity really quick and now almost all cars have parking sensors which is based on sonars.
- **GPS/GNSS:**
  GPS has developed for military use but quickly became popular for cars. Now most cars use GPS for positioning and navigation.
- **IMU (Inertial Measurement Unit):**
  IMUs are multi sensor devices which measure a lot of data, there are many types of IMUs some embedded, some external, almost every smartphone has IMUs. First device to be seen as an IMU is the basic compass, showing heading of the subject
- **Odometry Sensors:**
  Odometers are basically revolution counters and installed into every car since the first cars. Today these sensors have gone more advanced and provide more accurate and more variety of data.

2.5 Hardware

What makes driverless possible is the hardware, this is where raw sensor data turn into movement.

2.5.1 Why Special Hardware is Necessary

Hardware is integral for driverless; Software becomes useless if it is incompatible with the hardware. Software that is very capable on its own and a sensor mesh that is very detailed could lose all its ability if there is no hardware support. Hardware is also responsible for most of the power usage on the driverless system, so a very powerful hardware is a waste of space, weight and power if not used properly.

2.5.2 What Hardware is Available

With the commercialization of Driverless technologies, hardware designed specifically for driverless are becoming more common. In the early days of driverless, desktop computers and servers are used as hardware, nowadays installing and run hardware makes things much easier to integrate the hardware in to the cars ecosystem.

2.5.2.1 Nvidia

Nvidia offers easiest access and highest performance hardware for driverless application. These devices are powered by NVidia's newest Xavier processors and a GPU based system. There are two models from this line up these are Pegasus and Xavier; Pegasus is built for full autonomy of road cars and Xavier is built for level 2+ autonomy.

2.5.2.2 Intel

Intel's offerings are not consumer based. Thus, there is less information about their abilities and specifications. Intel focuses on big companies as their prime consumers. And instead of Nvidia, Intel uses FPGAs to accelerate and process the images.

2.5.2.3 Other Hardware

Autonomy hardware does not need to be too complicated. Even a simple microcontroller board could achieve some performance as the driverless system hardware. There are many options available for microprocessors in the market. These small but efficient microprocessors could not achieve the huge performance of the big computers of intel and NVidia but for a much simple application they are applicable.

2.6 Software

For driverless system, software is an extremely important aspect. All the detection and actuation happen in software side.

2.6.1 Simulators

Simulators hold a very large spot on software. They are the most computation demanding software in driverless since simulations not only detect, analyse and act but generate and control the environment as well.

2.6.1.1 CARLA Simulator

CARLA is a free, Unreal Engine 4 based simulator and seen as the most comprehensible simulator available. Roborace teams use this simulator to simulate their tracks and races as well. Being an open ware allows CARLA to be edited for the specific needs of developers.

2.6.1.2 Other Simulators

There are other simulators available also based on different engines and different needs. For example, Udacity formed their own simulator for teaching driverless, this simulator is much simpler than CARLA simulator but easier to use and program.

2.6.2 Control Software

Only creation of behavioural model is not enough for actuating the commands, for this purpose a middleware is used. This program controls the inputs and outputs and form a software ecosystem.

2.6.2.1 Robotics Operating System (ROS)

ROS is the most common middleware present for any autonomous and robotic system. This middleware acts as an operating system on top of the existing one creating a soft ecosystem and allows seamless integration of different programs and tools

2.6.3 Detection Software

Detection software is used to detect static and dynamic objects using different methods like image processing. Detected object data then sent to prediction software.

2.6.4 Prediction Software

Prediction software predicts which way to take and what manoeuvres to make regarding the objects detected from detection software. After planning has made actuation to make the necessary manoeuvres are sent to the actuator hardware.

3 Discussion

The discussion and comments made in the section are focused on Driverless Race cars especially Formula Student cars but also applicable to road car operations.

3.1 Developing Strategies

When developing Driverless there are a couple ways of implementation and road maps available.

3.1.1 Why Developing Strategies are Important

Developing a project like driverless requires a clear road map to follow to prevent being lost in details; also, to how and when to proceed.

3.1.2 What Kind of Developing Strategies Exist

For the purposes of developing driverless two methods of development are considered by the author to be the best. These strategies are used by two best driverless developers: GM and Waze. Each of the developers' approach to the problem have different strengths and weaknesses. Before selecting a strategy, the driverless developer should first determine the strengths and weaknesses of their available resources.

3.1.2.1 Software Based Development

This method is suggested to the developers who cannot afford hardware and sensors easily but have powerful computers to simulate. It has to be taken into account that basic

simulations don't require much computing power, but as the complexity of the simulations increases, more powerful simulation equipment becomes necessary.

3.1.2.1.1 Pros and Cons of Software Based Development

Pros of this development is being surer that the system will work and when something fails during implementation developer can more easily focus on a hardware failure. This development is ideal when starting a driverless project with minimal funds, since it requires only a powerful computer to start.
The cons of this type of development is that it requires most of the work done without a physical result, this may result in less funding to be arranged for the project. The late physical result also means lesser preparation to incompatibilities and an unknown real reaction in real life, no matter how accurate simulators are, simulator's realism has their limit.

3.1.2.1.2 Steps in Software Based Development

Software based development as the name suggests begins with the behavioural model of the car, this include how the car will behave in certain conditions. At this point there is very little physics involved since behaviour model is not the performance model.

One of the biggest and most successful driverless developer Waymo uses this method to develop driverless cars.

Before starting to develop the behavioural model, a preliminary analysis would be necessary. This thesis aims to provide this step. In this step developer analyses, which of the factors are needed to be taken into account when developing the model. Some factors mentioned in this thesis can be used simpler or outright neglected in favour of faster development and simplicity.

After the first step a basic behaviour model can be written according to the variables set in the preliminary analysis. When writing the behavioural model, a fault model should be crated. A *fault model* is a Fault tree, where the results of component failures are predicted and according to this failure adjust the behavioural model to counter the results of the failures.

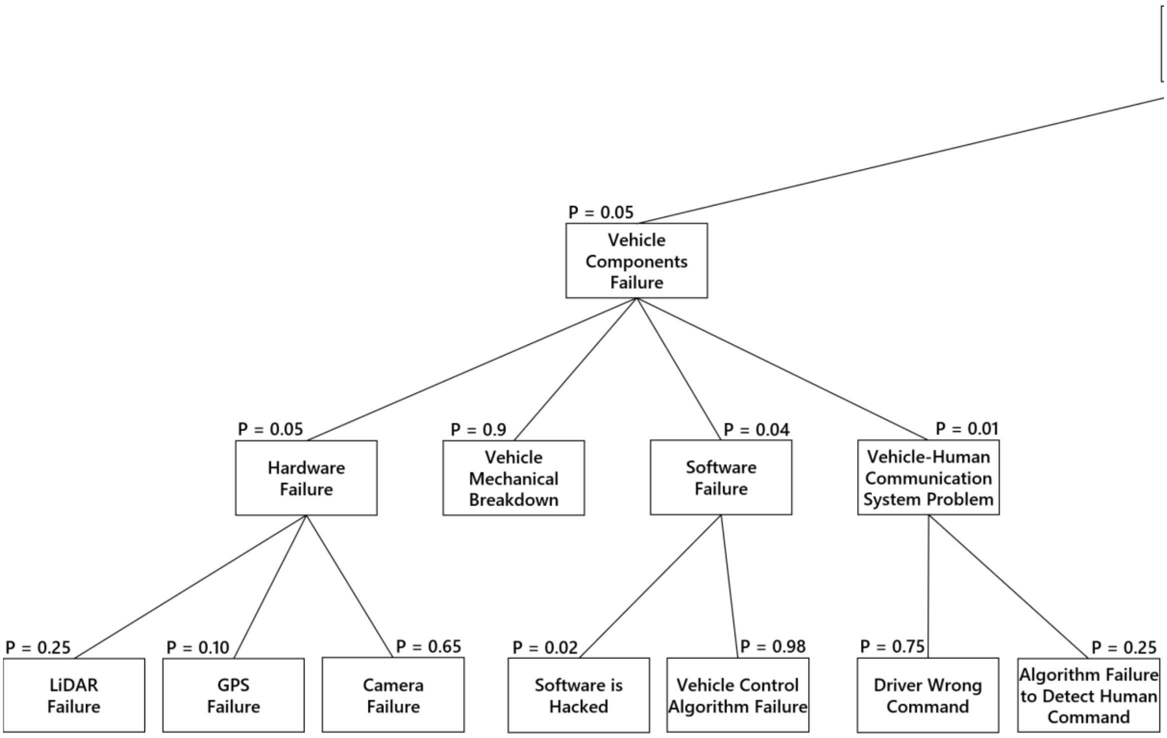

Figure 2. An Example of Fault Tree. (Introduction to Self-Driving Cars, Coursera, 2019)

After Fault tree is made up and all the necessary faults countered, it is recommended that Design Failure and Effect Analysis be performed. This analysis gets into more detail of failure and effects, in the previous fault tree, effects were caused by failing system components and generating scenarios. In this analysis, what components needs to be damaged of faulty to cause predetermined effect is looked into. There are certain conditions which have to be made sure that the system will perform in a desired way. With this analysis, key actions like these can be altered in a safer way and as the regulations require.

It is key to simulate after every alteration. No matter how extensive research and analyses performed nothing can be certain. To counter this uncertainty, extensive and long simulations need to be run.

3.1.2.2 Partial Implementation Based Development

Partial Implementation is a strategy more devised on “doing” rather than analysing and simulating like software-based development. This strategy is best suited for developers who have good funding, easy access to necessary hardware and is not very good with software. This strategy, if not executed careful enough, is dangerous and can result in

damage on the vehicle and/or injury. The developer who wishes to follow this strategy will receive faster physical results but proper consideration has to be made on the safety and reliability.
One of the biggest companies which employs this strategy is GM.

3.1.2.2.1 Pros and Cons of Implementation Based Development

Pros of this kind of development are: since at every improvement is done with an implementation, this strategy provides more “physical” results, making public to see the product better, helping with finding more funding with project. With more implementations are made, the data gathered is realistic which produces much accurate results than any simulation.

Cons of this strategy are: It is expensive since it requires the hardware necessary and any change in the shape, placement or type of the sensor means redesigning and building the system again. Due to production is more rushed than a software-based development less simulation and analysis are made, causing in unwanted reaction in some cases.

3.1.2.2.2 Steps in Implementation Based Development

This strategy is an iterative strategy, which means that every time it gets better, and iterations are to be made until satisfied.

It all starts with performance testing. This test is done before any development, making an estimation on what will be needed and making sure that the hardware is compatible, powerful enough to process all the data and respond fast enough. This testing includes benchmarking the hardware so it can process the input from the sensors and output actuations fast enough. On this test all sensors are also tested on their sensitivity and refresh rates.

After this step to fill up the incompetency found during performance testing requirement validation is performed. Any required components are determined along with any improvements that will be made. After satisfied with the performance, the developer can start implementing the driverless software or edit the software.

Then a fault injection test is performed. This test is similar to the fault tree in software-based development. Conducting this test requires taking out one of the components or simulate damage to see how the system will react and compensate for the fault. Just like a fault tree after each test modifications are made to prevent any unwanted action.

After planned fault injection testing developer must prepare the system for unplanned and unforeseen events also. This is called *intrusive testing*, where car is tested outside its determined parameters. For example, rain testing is done on fault injection test but a lightning strike on the car is done on intrusive testing, since it is a rare event that is very unlikely to happen or an electromagnetic disruption.

After the intrusive testing consistency is tested during durability testing, this testing can be seen as an endurance test for the system, making sure that the system acts the way it is supposed to every time.

Last, simulation-based testing for the behavioural model is conducted, to make sure that the car will behave as planned and intended on track. This test is done in the same way as software-based development, with only difference being this simulation testing is not as detailed and complex as the software-based counterpart.

In the end of all these tests found faults, glitches and mistakes are fixed and patched and another iteration is made this time setting the bar higher. For example, for the first iteration a longitudinal acceleration can be made, on the second iteration deceleration can be added, on third low speed lateral control, keeping the advance at every iteration.

3.2 Evaluation of Driverless Education

To develop driverless first how to develop it needs to be learned. Usually universities with graduate studies have similar fields and subjects on developing driverless of robots, these two subjects share a lot in common and most driverless developers come from robot development. For this reason, there some material exists which can be used for developing driverless.

3.2.1 Importance in Education in Driverless

Driverless requires education before starting to develop it. This unlike most software of hardware development, any mistakes when developing driverless could lead to crashes

which may result in injury. So, a developer for the driverless vehicles must know the basics, the rules and where to be careful.

3.2.2 Comments on Online Courses

Many subjects required for driverless cars are not covered in undergraduate courses. Because of this one needs to get online courses. Online courses featuring driverless represent themselves as nanodegrees. There are two courses stand out from the rest when developing driverless:

3.2.2.1 Udacity

This course focuses more on development and how to develop faster, although it takes faster course while developing its theoretical aspect is more limited. This course is recommended for developers who have less time and wants speedy response from their work.

3.2.2.2 Coursera

Coursera partnered with University of Toronto to present this nanodegree. This course focuses more on understanding the background and features more in depth explanations. This course is recommended for Developers who have time and wants to better understand the aspects of developing driverless.

3.2.3 Written Material

Just like any subject there is some written material available to develop driverless. These materials vary from web pages, which explains step by step instructions of developing driverless, to textbooks written by university professors, which offer better understanding of driverless cars.

3.2.3.1 Master's Thesis'

Unlike most of the material available, there are Master's Thesis' can give a developer better understanding on driverless in Racing and Formula Student. Master's Thesis' are usually detailed and requires some previous knowledge. Some master theses even produced some open to public material to make development much easier. Such as works of AMZ Driverless team which has a GitHub repository including items which aims to help other developers.

3.2.3.2 Textbooks

Textbooks available for Driverless are usually the most detailed material available, although some previous general knowledge is required, they are good at explaining basics and very detailed on advanced subjects.

3.2.3.3 Web Sites

Web based materials provide very basic information and is recommended when small problems arise when developing, to look for solutions and fixes. This material is also limited because most driverless development is done by the companies and the information is classified but it is still possible to find solutions to specific problems.

3.2.3.4 Material from Other Teams

Other teams from Formula Student has provided with open license material for developers for other teams to utilize. These materials are limited in complexity and lacks some detail, but provides a good starting point for a driverless developer. One of the most useful materials from other teams is TU Delft's Formula Student Driverless GitHub.

3.3 Important Points When Developing Driverless

While developing driverless the developer needs to consider some elements to make the best performing system.

3.3.1 Physics of Cars

Cars, just like any object, is bound by the laws of physics. It is important for a driverless developer to understand these laws to get the best performance on the track. There is a lot of physics in play when we consider cars. We can divide the most important Physical aspects into:

- Inertia
- Tires
- Aerodynamics
- Internal mechanics

3.3.1.1 Inertia

Most basic physics that is applied to any object. It is based on Newtonian physics and effects the car in a very simple but important way. This refers to where the center of gravity and how much the car weighs. A heavy car needs more force to accelerate and to change direction. It also makes the care stable on a straight line when going at high speeds. Center of gravity determines the way car reacts to the forces applied to it.

3.3.1.1.1 Acceleration

For the first implementation of the model we are concentrating on the acceleration and deceleration event. This requires using tires more on longitudinally than laterally, which requires more torque to be delivered to the tires.

3.3.1.2 Tires

Tires are the second most important physics that effect the car. Since they are the only device which connects car to the ground, all major forces to and from the car are applied via tires. Understanding tire physics allows developer to control the car better. Acceleration and deceleration become more efficient and faster. Turning becomes more precise.

3.3.1.2.1 Torque

Torque is the key factor in movement in cars since tires move according to the torque they receive from the motors. Longitudinal tire slip also occurs according this torque. The more torque delivered to the tires means faster acceleration and higher speeds.

3.3.1.3 Aerodynamics

Aerodynamic forces have gained more importance in the last 30 years than ever before. Using Aerodynamic forces to the best and finding the balance between low drag and more downforce is the work of an Aerodynamics engineer and to get the best performance from the work on Aerodynamics developer should work together with this engineer to design the system that understands how much downforce and drag does the car has. With more downforce sharper turns can be made, more force can be applied to the tires. With more drag, more power is needed to be spent to accelerate the car to higher speeds

3.3.1.4 Internal Mechanics

Internal mechanics is usually disregarded when designing a driverless system. This is due to the system using the wheels as a measurement and not the engine itself. But understanding basics of engine dynamics allows system to utilize best engine performance (power transmission from the engine to the tires). Internal mechanics should also include suspension, since the tires are the only element that connects the car to road suspension allows tries to keep contact to the ground.

3.3.2 Important Aspects

3.3.2.1 Throttle Response

Throttle response varies from engine to engine. But for the sake of simplicity we can divide it into two engine types, electric and combustion.

3.3.2.1.1 Combustion Motor Throttle Response

Combustion engines have been used since the creation of the car. And it improved in many different ways throughout history. This history of improvements and many other variables effect the performance of the combustion engines. Usually it is expected that combustion engines provide low torque at low RPMs and higher torque at higher RPM. Depending on the topology of the engine, where maximum torque generated changes.

3.3.2.1.2 Electric Motor Throttle Response

Torque in Electric motor cars is instant and constant, what varies is RPM for these motors. It should be considered that at high RPM torque drops but it is easier to predict the behaviour of the electric motors. Although very advantageous at lower RPM, electric motors currently cannot match the power output and the torque of combustion engines.

3.3.2.2 Power Delivery

Engine power is not enough to make a car fast, it is very important also to deliver the power of the engine to the wheels. And for this purpose, we have a couple of ways, but mainly two types of drive delivery are used these are geared and direct drive.

3.3.2.2.1 Direct Drive

This kind of drive is usually associated with electric motors due to their consistency on applying constant torque. This is also the most efficient way to deliver power, since there is no loss of power due to friction and movement of gearbox equipment. It requires high consistent torque to be effective. It adds ability to drive each wheel individually if every wheel is drived with their own motor. The cons of this type of drive is the speed, which is limited to the rpm of the motors. You cannot adjust the wheel speeds and the behaviour of the acceleration. For example, gear ratios cannot be adjusted like gear driven cars, so high speed and acceleration is dependent on the motors used.

3.3.2.2.2 Geared Drive

Geared drive is the most conventional way to drive the wheels. This way includes a geared system which allows for wider range of operation. Since the limit is not the engine itself more of engine torque can be converted into wheel power and higher speeds can be achieved. Also allows for gear tuning and more modifications. With the current technology the losses in the gearing system is very much reduced but couldn't be nullified.

3.3.2.3 Tire Slip

Tire slip is the most common way for cars losing control. Wheels lock up when breaking making the car slide unwittingly, to burnout where tires spin without producing any acceleration. These consequences all occur because of the tire slip.

3.3.2.3.1 Full Throttle Tire Slip

At instant full throttle it is common for tires to slip and burnout. It is relatively hard for geared system to have such a reaction, considering gears are changed sequentially, but on a direct drive system it is almost inevitable. To prevent this, throttle needs to applied incrementally, same with breaks. If sudden hard break gets applied wheels locks and car starts to slip preventing braking.

3.3.2.3.2 Tire Slip Acceleration Curves

Tires don't slip until a certain acceleration limit, finding this limit is very hard and requires very complex equations so almost always guessed near a general value.

3.3.2.3.3 Incremental Throttle

To prevent tire slip on acceleration we apply throttle incrementally. How these increments are set depends on tire physics but a simple approximation can be made. The curve which we apply throttle can be set linearly, logarithmically and finally exponentially. Which curve to be used depends on topology and the strategy of the car and the team around it.

3.4 Sensors

Sensors are used for the Driverless car to react to the road conditions and outside elements. Each sensor has their own advantages, disadvantages.

3.4.1 Sensor Types

3.4.1.1 Cameras

Cameras are the main sensor of perception and can be used in many different forms. Most common form is to use it as a 2D image output then running image processing to make sense of the data. This method provides very limited information about the surroundings since it cannot provide any depth. Two cameras can be used stereoscopically to provide some depth. There are driverless systems that use only cameras and computer vision to navigate cars.

Important aspects when selecting cameras are:

- **Resolution:** Resolution of the camera determines how accurate we can receive information about the objects. It should also be taken into account that high resolution cameras require higher computational power to process leading to heavier weight, high energy consumption.

- **Field Of View (FOV):** FOV in cameras determine how much zone can a camera sees, which is usually a conical shape. At the same resolution, camera with low FOV provides more detail but very limited surrounding, while the camera with high FOV provides less detail but is able to see more. There are cameras with 180-degree view, using fisheye lenses, these cameras need some software processing before truly producing a 180-degree image.

- **Dynamic range:** Dynamic range of a camera is how much light can the sensor detect. This is the difference between the whites and blacks. If a camera's dynamic range is too low, any bright object or space will

appear white, while darker objects or shadows appear black. As the dynamic range of the camera increases, more objects can be detected but high dynamic range cameras are expensive. One way to fight this is High Dynamic Range (HDR) capturing, HDR is a software-based solution which combines more than one exposure to expand dynamic range, this reduces the need for a very expensive camera but requires more images to produce a single final image. Disadvantages of HDR is it requires high refresh rate camera and image processing power to combine all images instantly this increases the computational hardware needs.

3.4.1.2 Laser Imaging, Detection And Ranging (LIDAR)

LIDAR generate three-dimensional maps of the environment around them, which is important to perceive scene geometry. These sensors can also provide crude colour so that it can be used as a low-resolution camera alternative. LIDARs operate using light but this sensor doesn't get affected by environment's light condition this means that LIDARs provide their own light to detect environment so if the environment is dark these sensors still operate efficiently. When LIDARs are first used there were only mechanical LIDARs, this meant that there is a moving mechanical part. These days Solid State LIDARs are more common, these LIDARs are smaller in size compared to their mechanical counterparts. Solid State LIDARs are also more durable since they require no mechanic movement to operate.

Important point about LIDARs are:

- **Number of beams:** Just like the cameras, LIDARs have resolutions. Vertical resolution for LIDARs depends on their number of horizontal lines, called rays, that LIDAR scans. The number of rays goes with powers of 2 such as 4, 8, 16, 32, 64, 128. At the time of writing this thesis highest resolution consumer LIDAR has 128 rays.

- **Points per second (PPS):** PPS responds to the horizontal resolution, how many points from each ray have gathered in a second. Although PPS is the horizontal resolution of the LIDAR, this resolution is also dependent of the rotation rate which is the next subject.

- **Rotation Rate (RR):** RR refers to the RPM of LIDAR. RR acts as resolution when combined with PPS and refresh rate at the same time. More zone can be covered quickly and instantly with high RPM. Combined with high PPS, it provides higher resolution.

- **Detection Range (DR):** DR is the range of how far does the LIDAR can detect objects, this is relevant to the output power of laser on the LIDAR.

- **Field of View (FOV):** As with all sensors LIDARs have a FOV. Most LIDARs have wide FOV mostly 360. Narrower FOV LIDARs exist as with FOV of 270, 180, 90.

3.4.1.3 Radio Detection And Ranging (RADAR)

RADAR has developed in the early 20th century, and over time it becomes more accurate. Main principles of RADAR are similar to LIDAR, their difference is their use of electromagnetic spectrum. LIDAR uses closer to visible light of the spectrum while RADAR uses lower wavelength of the spectrum. Using Radio signals for detection allows detecting objects in low visibility conditions at the cost of resolution.

Important points about Radars are:

- **Range:** Radars have long range compared to other sensors. Range of a radar depends on the power of the transmitter and sensitivity of the receptor.

- **Field of view (FOV):** FOV in radars are separated into two main types, Wide Field Of View (WFOV) and Narrow Field Of View (NFOV). WFOV radars provide wider field of view at the cost of short range and inaccuracy. NFOV RADARs provide long range detection and better accuracy in a narrow FOV. This type of radars is used in high class cars for adaptive cruising and automatic breaking.

- **Position and Speed accuracy:** Position accuracy refers to the resolution of the RADAR. Speed accuracy refers to the accuracy of the distance measurement from the detected object.

3.4.1.4 Sound Navigation And Ranging (SONAR)

SONAR is good for Short-Range Detection. They are low cost, and good on parking manoeuvres.

Important Points about sonars are:

- **Range:** SONAR ranges in cars are low. They are mainly used as close proximity parking sensors.
- **Detection Field of View:** SONARs have a predetermined field of view where they can detect objects. This FOV is usually around 45 to 90 degrees.

3.4.1.5 Global Positioning System (GPS)

GPS is used to determine where a car is relative to the earth.

GPS Measures:

- Position: GPSs main function is to locate the car in the world.
- Velocity: With using the changes in the position over time, GPS can measure the velocity of the car
- Time: GPS also provides world standard time to calibrate sensor and map data
- Heading: GPS can provide crude heading using change in position. Combined with Inertial Measurement Unit (IMU) more accurate heading and speed can be calculated.

3.4.1.6 Internal Measurement Unit (IMU)

IMU is comprised of accelerometer and inclinometers. This sensor provides basic movement data for the car.

IMU Measures:

- Angular Rotation Rate: Rate which the car changes its heading.
- Acceleration: using accelerometer, acceleration on different axis can be measured
- Heading

3.4.1.7 Odometry Sensors

Odometry Sensors are the cars internal measurement sensors. All cars have basic odometry sensor: Odometer (speed gauge).

Odometer Measures:

- Wheel Velocities: Odometry sensors can measure each wheel's turning rate, as well as other information such as tire pressure.
- Orientations: Front tire orientation can also be measured by odometry sensors

3.4.1.8 Electronic Control Unit (ECU)

ECU is installed on every car since late 1980's. These control units are basic computers which control engine. All data gathered on the car is sent to the ECU which in response handles cars basic functions. ECU data can be accessed with universal OBD port.

- Engine data: Engine RPM, instant power, instant torque and many more engine related information can also be accessed with odometry.

- Car condition: Fuel level, oil level, fuel consumption can also be measured with these sensors.

3.4.2 Sensor Usage

Previously mentioned sensors can be used in different combinations to create a more reliable, complete sensor mesh. Each sensor has their own advantages and disadvantages, using a combination of sensor allow as to utilize all sensors advantage while compensating for their disadvantages.

3.4.2.1 Camera

Most basic advantage of camera is its versatility since it is the closest sensor to resemble the human eye. It can be used to detect all objects on medium to short range. Two or more cameras can be combined to create stereoscopic image which adds distance to the otherwise 2D captured objects. Cameras can also identify between dynamic and static objects using image recognition.

Disadvantages of the cameras are: At low light conditions (i.e. night time) they provide with very little to no data. Most Cameras have limited FOV so to get 360-degree coverage more than one camera needs to be used. At low visibility conditions (i.e. fog, rain, heavy snow, dust storm) cameras can provide with only short-range data and depending on conditions, lenses of the cameras maybe blocked, cameras may provide with no data at all.

3.4.2.2 LIDAR

LIDARs provide wide FOV by default, and they are not dependent on light conditions like cameras while also providing depth in their output, it is much easier to create a 3D map around the vehicle.

Disadvantages of LIDARs are: Their resolution, although improving, is limited. Just like cameras LIDARs are susceptible to low visibility conditions. LIDARs are also expensive compared to cameras.

3.4.2.3 RADAR

RADARs provide relatively narrow FOV but compensates by providing long distance detection which can be used to detect objects far away, this ability is especially useful on high speeds since with a detection of object far away can lead to taking precautions before it’s too late. Wide FOV RADARs can be used as backup for LIDARs since RADARs don’t get affected by low visibility conditions as much as light sensors.

Disadvantages of RADARs are: Low Resolution, which prevents accurate guesses of objects. RADARs are also expensive equipment.

3.4.2.4 SONAR

SONARs for cars provide adequate FOV on short range, other than that there is very limited use of SONARs in cars. Although their uses are quite limited, SONARs are very cheap and could be used to provide good all-round crash detection and close quarters manoeuvres.

Disadvantages are: Only useful in short range. No detail of surrounding objects can be received.

3.4.2.5 GPS

GPS Provides accurate data for the placement of the vehicle. This data can be used in many ways, one of which is accurate speed readings, calibrating time on the car. Unlike other sensors mentioned GPS does not provide drivable data.

3.4.2.6 IMU

IMU sensors are mainly used to provide feedback for the actuators and situation assessment. Depending on the calibre, these sensors can be very accurate and can be used with GPS for improved accuracy.

3.4.2.7 Odometer

Odometry sensor on each wheel provide feedback for actuator and control. This way actuator can determine if an output is having the desired effect, Odometry sensors are also used in Traction Control (TC) combined with IMU data

3.4.2.8 ECU

ECU provides all information about engine, which could include odometry data as well. Usually there is no need to access ECU for developing driverless but if the driverless system requires to be more integrated with the car OBD port can be used to gather necessary data

3.4.3 Sensor Placement

3.4.3.1 Visual Sensors

Cameras and LIDARs are usually placed on top of the vehicle to provide better view and to avoid material that is picked up from ground. For a Formula car this area is very limited and some teams place these sensors on roll hoop, this provides best access for LIDAR to have 360 view but this method also makes the sensors very shaky, to counter this problem LIDARs and Cameras are placed in the front, while limiting the LIDARs FOV

3.4.3.2 RADAR

RADARs are placed right in front of the vehicle since most of the time vehicle is headed. It is preferable to place RADAR in the very front of the car to prevent misreading from cars body.

3.4.3.3 SONAR

SONARs are not necessary for Formula cars. But if a team decides to include these sensors, they should be placed on the end of the body work, since sonars only provide distance data, any piece of cars body in SONARs FOV will result in a misreading.

3.4.3.4 Internal Sensors

Internal sensors include GPS, IMU, Odometry sensors and ECU. These sensors, except for the odometry sensors, can be placed anywhere in the car. Most advantageous spot for these is where the ECU is or where the Computational Hardware is, since this both units are provided with Low Voltage DC (LVDC) already. Odometry sensors are placed on the wheels, usually on the suspension elements.

4 Conclusions

This work aimed to provide a starting point for students and developers who wish to develop Autonomous Vehicles and to understand the main concepts behind it. While also providing a good resource evaluation according to needs and available material of the developer.

The developer armed with the knowledge found in this paper can start developing the driverless system using the road map provided with this paper. Bearing in mind that Driverless development is not an easy task and will take time, effort and economic resources. Since this work acts as an introduction and road map a certain conclusion cannot be drawn except for that driverless is a complex subject with need of very deep understanding and material.

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