

The University of Western Australia
School of Electrical, Electronic and Computer Engineering

Environmental Mapping and Software Architecture of
an Autonomous SAE Electric Race Car

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Abstract

This dissertation covers the author's work on the development of the control system, software architecture, environmental mapping and visualisation system of an Autonomous Electric SAE car at the University of Western Australia.

The UWA REV Autonomous SAE Electric Race Car Project is a platform for students to explore and develop modern electronics and automation systems, and spans multiple disciplines including electronics, power systems, software design, and computer science. This year the project team has been working to extend the autonomous driving functionality of the Electric SAE Race car to be suited to the racing conditions set by Formula Student Germany. This extension involves implementing the ability to autonomously drive through a track delineated by traffic cones. On top of this the team has aimed to improve the platform to facilitate the ease of future developments in part through the author's work in building a modularised software system with the intention of replacing the previous system.

The design considerations, implementation processes and test results of this work is discussed.

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Thomas Drage for his knowledge, guidance and support.

My friends and family for providing me with support over the course of the year.

Nomenclature

SAE	Society of Automotive Engineers
REV Project	Renewable Energy Vehicles Project
UWA	University of Western Australia
LiDAR	Light Detection And Ranging
LiDAR: Raw Data	The series of 3D data points provided by the LiDAR that denote the position of light reflective material in the LiDAR's field of view.
LiDAR: Object Data	The data provided by the LiDAR that denotes the position, size and classification of objects as interpreted by the LiDAR's internal data processing.
IMU	Inertial Measurement Unit
GPS	Global Positioning System
PID Controller	Proportional-Integral-Derivative Controller
ASIO	Asynchronous Input/Output
Protobuf	Google Protocol Buffers Tool
SLAM	Simultaneous Localisation and Navigation
FSG	Formula Student Germany
FSD	Formula Student Driverless
ANN	Artificial Neural Network

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1 Introduction

Autonomous navigation in automotive vehicles has the potential to significantly increase the safety and energy efficiency whilst reducing transit times. Designing a car to consistently drive safely in various contexts such as public roads poses many challenges including sensor fusion, data analysis, sophisticated control algorithms and reliable safety systems. Beginning in 2009 The Autonomous SAE Car project at the University of Western Australia, led by Prof. Dr. Thomas Bräunl has developed a drive-by-wire, electric SAE car with autonomous capabilities with the goal of expanding its abilities to include race track navigation and urban driving. In 2013 considerable progress was made by Drage who developed the safety systems, controllers, road-edge detection and navigation systems capable of autonomously driving through recorded GPS waypoints [1]. The path planning was improved by French [2] in 2014 and again in 2015 by Churack [3] along with improvements to the road-edge detection.

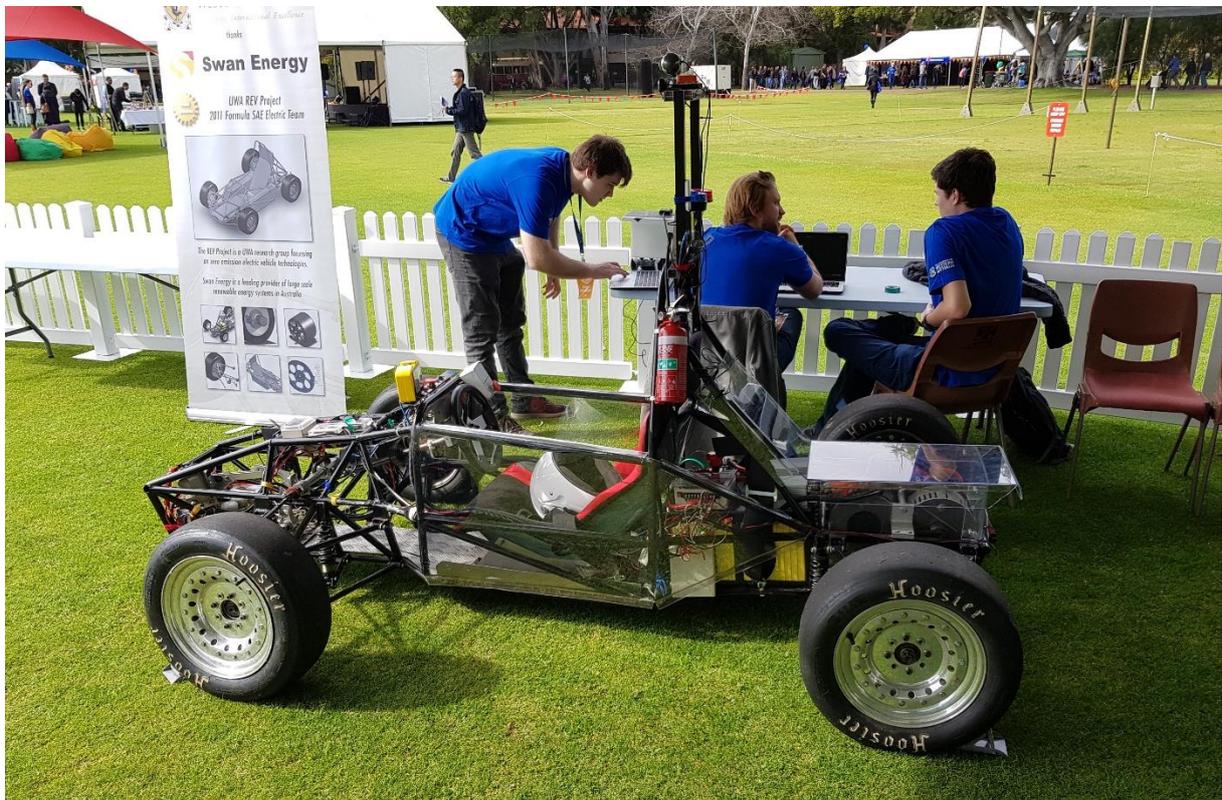


Figure 1: The Autonomous SAE Electric Race Car.

1.1 Motivation

The development of an autonomous vehicle provides a platform for the study of robotics, control systems, sensor integration, data analysis, software engineering, and automotive electrical hardware design. On top of this the task of developing a driverless race-car provides a challenge as safety considerations in both hardware and system control must be prioritised whilst maintaining a goal of high performance.

1.2 Goal

In 2017 Formula Student Germany [4] announced the inclusion of a new competition; Formula Student Driverless. FSD is an international student-based competition to judge the performance, engineering practise and design of driverless cars based in Hockenheim, Germany. The intention of the REV Autonomous Electric SAE Car Team was to make progress towards preparing the car for the requirements [5] of the FSD competition in coming years as it is expected that these specifications would become an international standard for driverless competition. Particular focus was placed on navigation which would involve developing the navigation system to include cone detection as the FSD track is a cone-delineated circuit as seen in Figure 2.

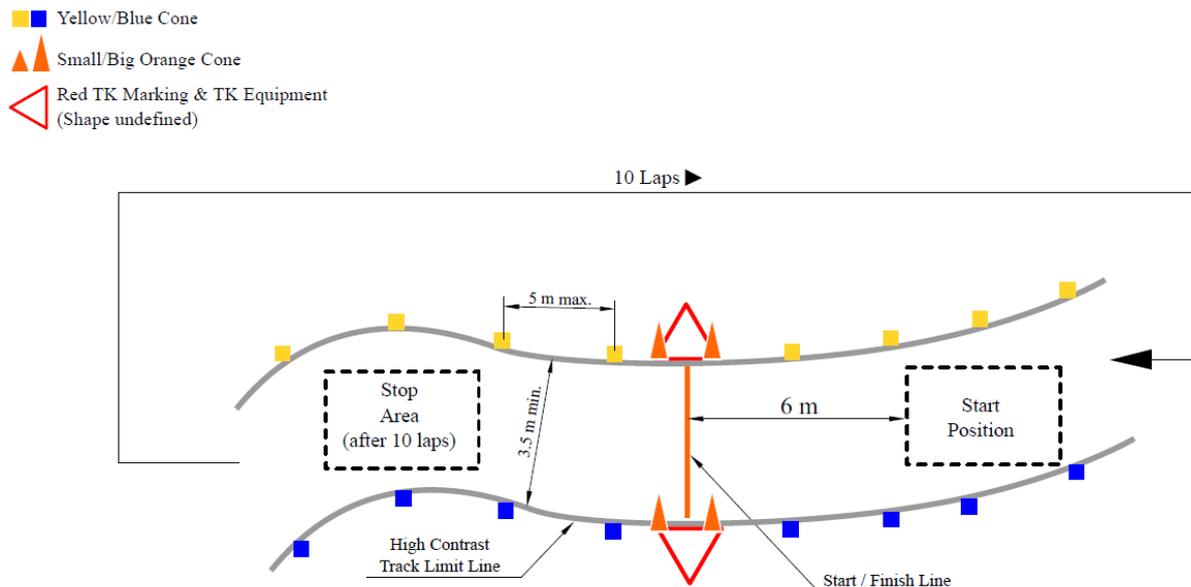


Figure 2: Diagram of the cone-delineated track parameters in the FSD specification book. Source: [5]

This dissertation outlines the author's work in designing an updated control system and corresponding software architecture, and mapping algorithm suited for cone detection. The author discusses the benefits of the design, the results of the implementation of the mapping system and potential future improvements arising from this work.

2 Literature Review

Autonomous driving has been an increasingly popular area of research over the last 30 years as the field grows and more applications for autonomous vehicles are being explored and implemented. Autonomous cars utilise a combination of control systems, sensors, actuators, and computer algorithms in a closed-loop controller to achieve various goals including exploration [6] [7] [8], speed [9], and safety [10]. Relevant literature in the control systems, software architecture and environmental mapping of autonomous vehicles is discussed below.

2.1 Control Systems and Software Design

The control pipeline of autonomous systems are often coupled to the software architecture as the control design decisions effect the software implementation. The 2005 DARPA Grand Challenge; a competition set by DARPA judging the speed with which autonomous vehicles could navigate a 142 mile long off-road track, was won by ‘Stanley’ an autonomous vehicle whose development was led by Stanford University [11] and represented a major step forward in the field of driverless cars.

2.1.1 Control

The control structure used an extension of the Three Layer Architecture discussed in [12]. This architecture details the use of three layers of control:

Reactive A low-level control layer responsible for effecting changes based on a rapid feedback loop. Example; a PID controller taking wheel speed inputs used to maintain vehicle velocity.

Executive Responsible for providing instructions to the reactive layer based on commands given from the deliberation layer. The processes controlled by the executive layer usually have fast loop speeds (~1 s) and may include sensor interpretation and mapping.

Deliberation Responsible for high level problem solving and solution generation such as calculating an optimal path around a race circuit based on the given map. This process usually has high computation times therefore updates infrequently.

The team behind Stanley [10] implemented an extension of the Three Layer Control system. The system architecture was divided roughly into six categories; Sensor Interfaces, Perception, Planning and Control, User Interfaces, Vehicles Interfaces, and Global Services. Sensor Interfacing and Perception were responsible for constructing relevant data abstractions from the sensors and belong to the Executive Layer. Planning and Control derives driving instructions and path planning from the Perception classes and are categorised as the Deliberation Layer. The Vehicle Interface systems are responsible for receiving the high level instructions from the controller and realising these goals by employing a rapid feedback control loop to govern the actuator outputs.

2.1.2 Software Architecture

The Stanley development team took inspiration from the 2004 winners and adopted the following philosophy: ‘Treat autonomous navigation as a software problem’ [10, p.66] To realise the desired control scheme in software the design team implemented a completely real-time, multithreaded system where each module runs separately of all others and all data transmission is done globally using timestamped data. This reduces the blocking of software processes as each individual system will continually run without stopping to wait for other processes to supply data. The timestamped nature of the data allows real-time control to be

applied and the guarantee that the data flow from sensors to actuators will be achieved with no repeated data.

To ease the software development and testing process the system was built in a modular way where subsections of the code could be run alone. Also, all data was logged and could be replayed through the control pipeline using a specifically developed replay module. Visualisation systems were developed to provide feedback on the systems state in both run time and simulation modes.

2.2 Environmental Mapping

The ability of autonomous robots to map their environment is another rapidly expanding area of research with the development of rescue robots [14] and other exploration based autonomous systems. The detail and speed of robotic mapping is dependent on the desired detail and intended navigation style.

2.2.1 Navigation Accuracy

For the purposes of navigation based autonomous vehicles it is often the case that low detail mapping is accurate enough for the path-planner and controllers to operate successfully.

H. Weigel et al. discuss the use of camera and LiDAR sensor fusing to deduce lane positions and track physical objects [13]. An internal list of detected objects is stored as the car moves. Objects detected by the LiDAR are compared with the existing objects in the internal map, unmatched objects are added as new objects while matched objects are fused together and the internal map is updated. The Mapper removes objects that are outside the observable area of the vehicle as they are no longer relevant for path planning. Objects that have not been matched in some time are also removed to reduce the impact of false positive object identification.

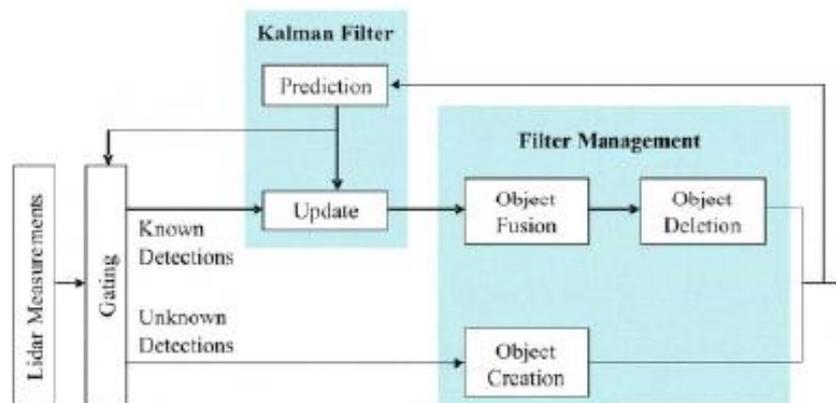


Figure 3: The object detection and integration algorithm. Source: [13]

2.2.2 Map Accuracy

Mapping using Simultaneous Localisation and Mapping has been employed in many exploration robots as a way to map environments without requiring odometry. In [6] and [7] the use of sonar and LiDAR with SLAM algorithms is discussed. In SLAM based systems the distance information provided by the sensors is used to construct a map of the environment. The map is used to plan the path of the robot, often towards unexplored areas. With each loop through the control process the world information is compared with the known system to localise the robot and expand the map.

3 Control System Design

The control system for the Autonomous car is required to navigate the vehicle around a bitumen circuit delineated by cones. In order to achieve this the car is first driven manually around the circuit to collect waypoints: intermittent position values of the desired path. When driving autonomously the control system must continuously interpret the data provided by the sensors and produce instructions for the motors. The car is a closed-loop control system using sensor data and the given waypoints as inputs and the cars position as the output.

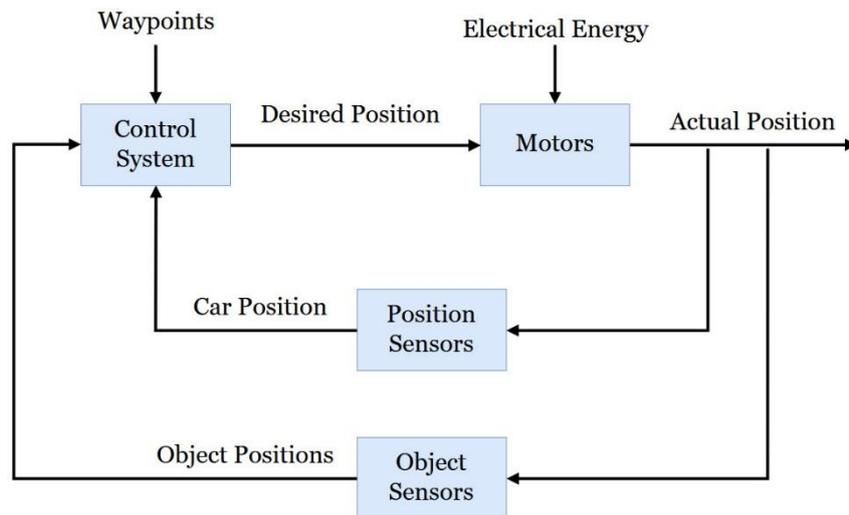


Figure 4: A simplified overview of the control scheme for the autonomous SAE car.

3.1 Requirements

The control system has three primary requirements:

1. The car must drive without human input around the intended track from start to finish.
2. The car must avoid hitting cones.
3. The car must be safe.

3.1.1 Navigation

As stated above, the car will be manually driven around the circuit prior to the autonomous lap. Once this is complete there will be no human input to the system and any human input necessitated by the other requirements (primarily safety) represents a failure to comply with this requirement. For this reason all primary safety systems and navigation controls must be designed to work autonomously.

3.1.2 Obstacle Avoidance

The described navigation system is capable of meeting the requirement of avoiding the cones because it attempts to drive a path defined by a manual drive during which no obstacles will be hit. However, the navigation system cannot precisely match the manual drive path as errors in the localisation cause noisy results for both the localisation of the waypoints and the

obstacles. For this reason the control system must incorporate a feedback loop to adjust its control parameters for error mitigation. This feedback loop consists of sensing the current car position and the position and dimensions of objects in the path of the vehicle.

The system is required to avoid all cones but must also avoid other objects that may be in its path and potentially moving such as people near the track. This requires that the desired path be updated regularly enough for reliable avoidance.

3.1.3 Safety

The safe operation of the system is the highest priority in each of the relevant subsystems of the car. Safety controls have been built into the hardware in both the electrical systems and the low level controllers. In the context of the control system it must be ensured that the car will not cause injury to people or damage to equipment. As this is the highest priority requirement, human intervention systems have been included and the expectation is for the autonomous instructions to be suitable for handling low magnitude threats, such as driving over cones, but greater threats will be managed by remotely disabling the control system and bring the car to a stop.

As the control system is required to avoid hitting any obstacles, the planner must provide suitable paths, safe driving at speeds that allow the path to be followed with reasonable accuracy and prioritising stopping over progressing through an object.

3.2 System Capabilities

3.2.1 Existing Features

At the beginning of the project the car was equipped with an integrated control system previously capable of navigating through GPS waypoints using GPS and IMU fused localisation. The LiDAR provided raw data used to detect road edges though the existing controller did not integrate road edge avoidance.

See [2] for a more in-depth overview of the existing systems.

Localisation

The localisation comprised of the fusion of GPS coordinates recorded at 1 Hz with acceleration and bearing data provided by the IMU. A Kalman Filter [15] had previously been implemented to improve the accuracy of the position data though the project members were not able to reproduce this functionality resulting in considerable inaccuracies in the GPS data. Position discrepancies of up to 5 metres were noted during testing.

The bearing of the vehicle was found by fusing the magnetometer readings from the IMU, which record angle against the earth's magnetic field, and the GPS tracking angle found by comparing subsequent GPS position readings. Due to the inaccuracies in the localisation system it was recognised that further development would be necessary to navigate through waypoints with low positional error.

Object and Road-Edge Detection

The system was capable of examining the object data from the LiDAR to display object positions as well as running a road-edge detection algorithm on the raw data. The road-edge detection algorithm takes the central data points and those near them and tests whether they meet flatness criteria. After compensating for the polar coordinate system of the LiDAR readings the road provides geometrically flat data within a tolerance range so no great changes in depth should be noted along the width of the road. Starting from the central readings, points at a wider angle are iteratively tested in a stepwise process where the correlation coefficient between the given point and the line of best fit to the road is considered at each point. The road edge is the point at which the correlation coefficient is the highest whilst the slope condition is still being met as the next point (the road edge) will diverge from the linear fit. This approach was improved with the implementation of a Kalman Filter which creates a time-averaged estimate of the road edge-position assisting in the prediction of the current road edge.

Control Algorithms

The existing control system uses a series of GPS coordinates (waypoints) to define the goal positions of the car. Waypoints are removed when the car comes within 2.5 metres of them at which point the next three waypoints are used to generate the intended movement of the car.

Heading

The steering control algorithm generates a cubic spline as the base-frame using the next three waypoints. A proportional controller is used to control the steering angle using the bearing from the GPS and IMU as discussed above to deduce the angle error.

Speed

The speed is controlled using two PID controllers, one for control of the brake and the other for control of the throttle. The desired speed is produced by assessing the intended turning angle of the base-frame with two options for desired speed being available based on whether the turning angle is above or below a given angle.

3.2.2 Features in Development by Others

The project team consists of 8 students with varying levels of involvement and responsibility. During the year features were assigned to students to develop in parallel with the author's work.

Odometry

To improve the localisation of the vehicle wheel speed sensors are being developed to provide high frequency odometry. Hall Effect sensors are used on the front two wheels to detect pulses caused by the motion of magnets attached to the wheels. These pulses are counted and recent measurements are averaged over time to provide current wheel speeds. The rear wheels are treated similarly though the pulses are provided by the encoders inside the motors. The steering angle is measured by reading the encoder output of the steering motor.

The intention of the odometry project is to provide a live, accurate approximation of the position offset and angle offset of the car with respect to its starting position. This estimation can then be fused with the existing GPS and IMU data to provide a potentially much more accurate localisation of the vehicle with higher update frequency.

Path Planner

An improved path planner is being developed with integrated object avoidance. A set of waypoints and a set of objects are provided to the path planner which generates a base-frame; a curve through the waypoints in the correct order. The manoeuvre generator takes the current position of the vehicle and generates a series of candidate manoeuvres. These manoeuvres are checked for collisions with objects and graded for quality. A higher quality manoeuvre may be defined as a path with lower curvature or higher distance from objects. The best candidate is selected and a series of car positions is derived from the path.

Vision

Prior to this year the only object detection system was through use of the LiDAR. The LiDAR is accurate but does not detect features such as object colour which may be useful as the interior and exterior cones will be different colours. An Artificial Neural Network is being developed that detects cones using video data from a mounted webcam. The neural network provides coordinates for cones it detects which can be fused with the LiDAR object data.

3.3 Design Considerations

The requirements stated earlier define the goal for the control system though there are other factors which affect the implementation. The goal for the Autonomous SAE Electric Car of driving through a cone-delineated circuit was set this year but prior development on the project both this year and in previous years was tailored to successful driving on public roads and race tracks without cones. This functionality should be preserved where possible and work done with the current goal in mind should facilitate future work in other contexts. Cone detection and avoidance is a necessity for success but the design of the control system should be such that it is easily expanded to handle other object detection scenarios.

The decision to have a manual exploration drive prior to autonomous navigation allows the existing path planner to be used while the new path planner is being developed as the manual drive provides the waypoints that are required. However, the exploration drive does not align with urban driving so the systems dependence on information gained during exploration is kept to a minimum and the control system is designed to be able to drive without an exploration drive.

The neural network that returns cone positions is specifically tailored to cone detection and cannot be extended to capture other object types easily. For this reason the object avoidance is designed to work without the vision system though it will lack the benefits of colour detection.

3.4 Design Process

After assessing the existing capabilities of the vehicle the following four control schemes were considered before beginning development:

- Control Scheme 1:** GPS waypoints are used to dictate the path of the car with live object detection used for object avoidance. The manoeuvre generator receives only the objects currently detected.
- Control Scheme 2:** GPS waypoints are used to dictate the path while object detection is achieved through application of the mapper which provides information of all objects in the system.
- Control Scheme 3:** Waypoints are created by assessing the object positions and planning a path through them. Object avoidance is inherently achieved through the waypoint generation.
- Control Scheme 4:** Localisation is achieved through object detection removing the dependency on the localisation sensors. The path is generated the same as Control Scheme 3.

Control Scheme 4 was ruled out early on as the urban driving requirements of the car did not align with a SLAM system and as development of the odometry systems was already underway. Control Scheme 1 was also ruled out as it had less potential for speed around the circuit and limited future improvements. Development began with Control Schemes 2 and 3 still in discussion; each uses a persistent mapper though Control Scheme 3 requires more sophisticated object analysis to detect left/right classifications of the objects.

At the time of writing the subsystems required to implement Control Scheme 2 have been completed and will be integrated together over the next few weeks for system testing. The inclusion of object-based waypoints has been rejected as accurate localisation is a prerequisite for both mapping and GPS waypoint generation so the benefits over using GPS waypoints for path-planning are minimal.

3.5 System Design

At the start of the exploration drive the angle and position of the car are recorded and used to define the origin. The car is then driven around the circuit storing regular position waypoints and positional data about the cones. A Baseframe is generated from the waypoints that encodes directional information for the manoeuvre generator and an initial manoeuvre is generated.

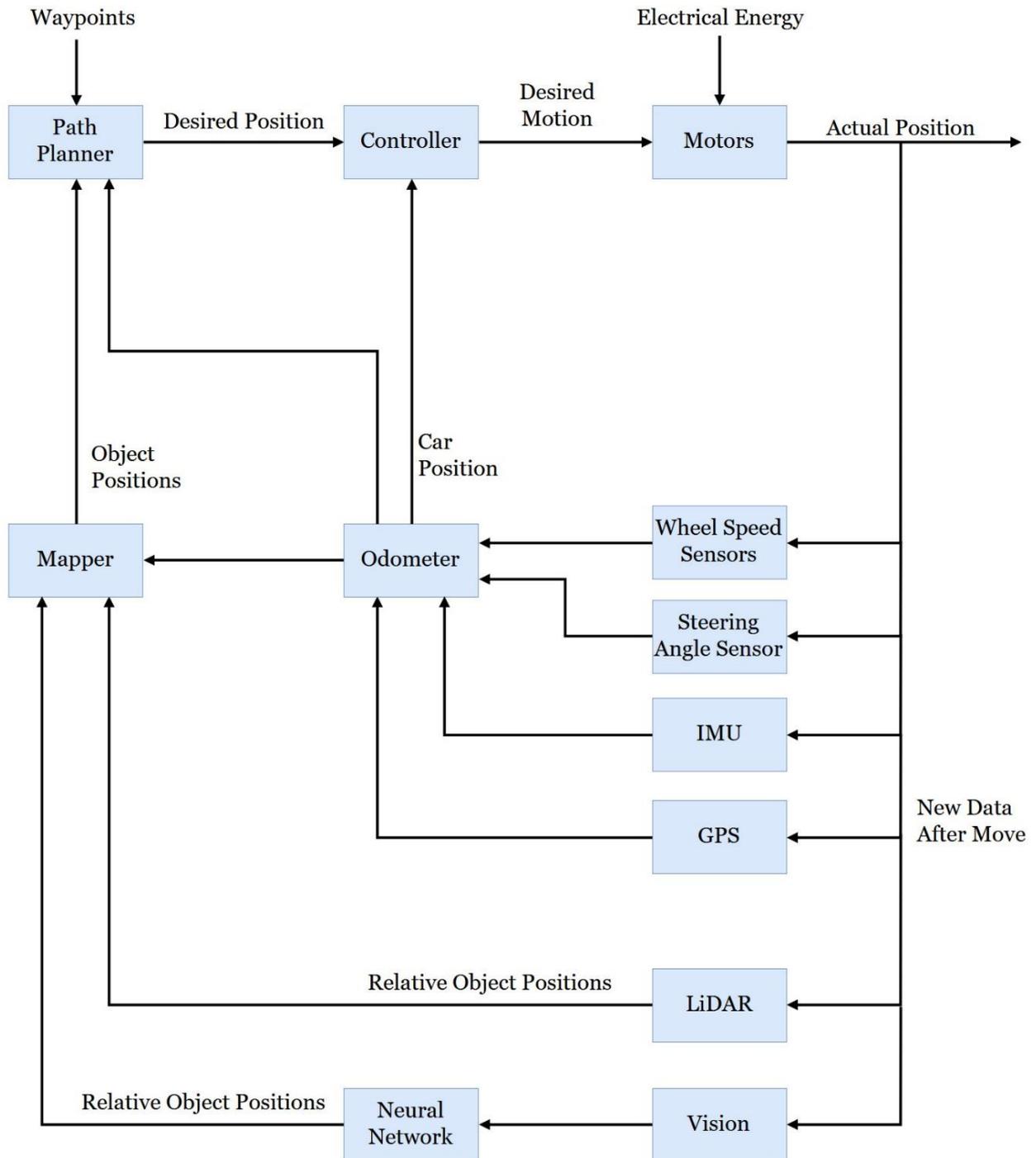


Figure 5: The control loop used when in autonomous drive mode of the SAE vehicle.

Localisation

The Odometer requests the data listed in Table 1

	Position	Velocity	Acceleration	Bearing
Wheel Speed Sensors		Yes		
Steering Angle Sensor				Yes
IMU			Yes	Yes
GPS	Yes			

Table 1: Localisation Sensors and the corresponding System Input Data

The data is fused to produce a current offset (x,y) pair and bearing with reference to the starting point of the cars exploration drive.

Object Mapping

The LiDAR object data and the object data from the Vision Neural Network is read in by the Mapper. All object data is transformed from the cars reference frame to the reference frame of the origin. The new object information is compared to the existing object data and used to improve the accuracy of the object localisation.

Path Planner

The object data and car's position are sent to the Path Planner which generates a collection of potential manoeuvres. These manoeuvres are filtered for collisions and paths not traversable by the vehicle and rated based on curvature criteria. The manoeuvre is discretised into a desired future configuration which is stored.

Controller

The control requests the desired position from the Path Planner and using PID controllers for the acceleration and braking, and a P controller to dictate the steering angle. These instructions are sent to the motor controllers which apply the electrical power.

This control loop is repeated until the vehicle reaches the end of the Path Planner Baseframe.

4 Software Structure

At the beginning of the project the software was run on a Raspberry Pi 3 with a Linux operating system. To facilitate the inclusion of computer vision, which requires higher processing speeds, this was replaced with an NVidia Jetson TX1 computer specifically design with parallel processing in mind. The existing software had not been designed in a manner that facilitated the introduction of new features and proved difficult to make design changes so a new software structure was designed with the intention of porting the existing functionality into it.

The software restructure process did not include re-writing the code responsible for the functionality; instead, it was the reorganisation of existing functionality into a new system framework that facilitated error detection, replacement of sub-systems and implementation of new features.

4.1 Design Considerations

The existing software was built to perform the intended functionality with limited consideration for software design and suffered from lack of management as the code-base was passed on to subsequent teams. This rapid prototyping development style is appropriate for producing functionality quickly but becomes problematic as the functionality grows, a problem further exacerbated when the members who understand the existing system no longer maintain it. The new structure was designed with the following considerations.

4.1.1 Separated Data Acquisition and Processing

Data acquisition and data processing are handled by separate systems. The data acquisition classes are an interface between the hardware and software and provide access to the most recent unaltered data on request. This allows the timing of data collection to be handled by the main program loop without introducing disruptions to the process as it waits for new data. Also, if the hardware is replaced, the only class that needs altering is the data acquisition class as it is decoupled from any processes that use the data.

Testing new features on the car is not always possible as software development may occur in times of non-operation of the vehicle. For this reason it is important to be able to simulate the processes of the car. By decoupling the data collection to other processes the raw data can be recorded and replayed during simulation to test additional functionality. Recording raw data as opposed to filtered data allows testing of the filters themselves.

4.1.2 Modularity

The Autonomous SAE Electric Race Car project is continued over multiple years with new developers joining and leaving the project often. Each developer typically touches on all parts of the system though the majority of their individual work will be focussed on the improvement or replacement of a single subsystem. This development behaviour is reliant on students being able to make changes to or replacements of a subsystem without compromising the others. To achieve this the software architecture must be modular: It must have individual functions contained to well defined sub-sections of the code-base. This structure encourages reduced dependencies between functions and the limitation of influence one section has over any other.

4.1.3 Simplicity

Many of the developers are not experts in software engineering or computer science and while the expectation is that students learn from their work incorporating tools with steep learning curves will ultimately reduce progress on the project over time as each new developer will need to spend more time learning the system instead of developing. Any tools incorporated in the system need to be justified with this in mind.

4.2 Design Process

A new copy of the existing software was created to develop the intended software structure whilst allowing further work on the existing system. Initially, an attempt was made to restructure the software by extracting subsystems into new structures whilst maintaining the ability for the code to be built and run. The road-edge detection was extracted and the new LiDAR reader was created, though this process exposed the high difficulty of altering the code structure.

An assessment of the viability of this restructuring method was made and it was decided to do a bottom-up approach: build the framework skeleton first and insert the existing functionality into the premade class structures. This approach allowed a clean design slate with far fewer limitations as the software architecture could be completely redesigned following sound software design principles whilst maintaining a runnable version of the code for separate development.

The first step was constructing a skeleton of the software: creating classes with empty functions that would define the ownership and inheritance structure, and the ordering of processes. Next, the LiDAR object detection, filtering, and visualisation were added and tested followed by the vision object detection system. At the time of writing the software structure is designed in its entirety though still requires the transplantation of core functionality before performance testing can commence.

4.3 Software Design

The software system is broken up into different tiers of objects that have restricted access to only the classes that they own with the exception of a few global utility data structures. This acts much like a traditional corporate structure; few members exist at the top and have high level control over the system and dictate the distribution of work by giving commands to managers of different sectors who in turn distribute it to the lower level workers who specialise in one job.

Tier 1 - Main

The highest tier there exists only one class, the main class that controls the high level flow of the program and owns manager objects that handle generalised tasks such as data acquisition, mapping, and path planning etc. The movement of data at lower levels must go through a common higher tier node as opposed to being passed directly between low level classes to stop the coupling of functions. A generalised overview of the top levels can be seen in Figure 6.

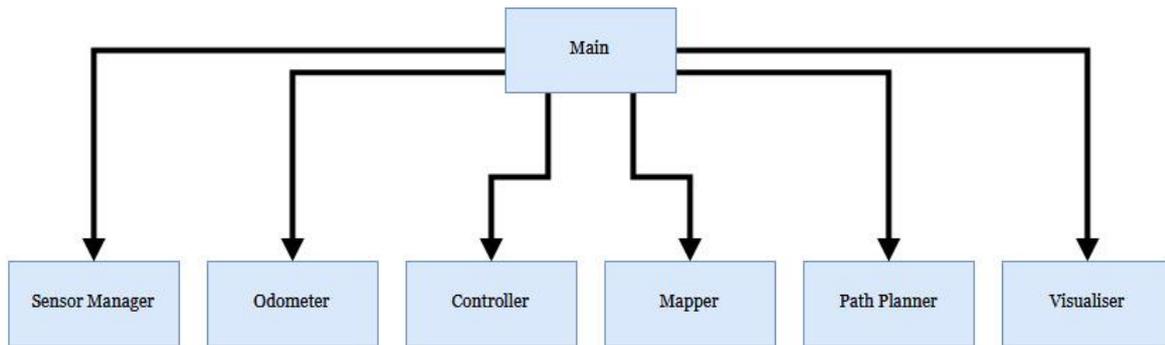


Figure 6: Class ownership diagram of the Tier 1 and Tier 2 classes.

The main class is responsible for dictating the control flow as discussed in section 3 and the movement of data between the sub-systems. For example: The Visualiser uses object data provided by the Mapper, this information is requested by main and passed to the Visualiser as opposed to the Visualiser directly requesting it from the Mapper. This allows the Mapper to be altered or replaced without needing any changes to be made to the Visualiser as long as the data by the new Mapper is provided in the existing format.

Tier 2 – Sensor Manager

The Sensor Manager is responsible for requesting data from the individual sensors who in turn interface with receiver classes which handle the acquisition of information from the hardware. The various receivers run in separate threads to the main control process and update local data variables when new data comes in which guarantees that the Main class always has access to the latest available data on request.

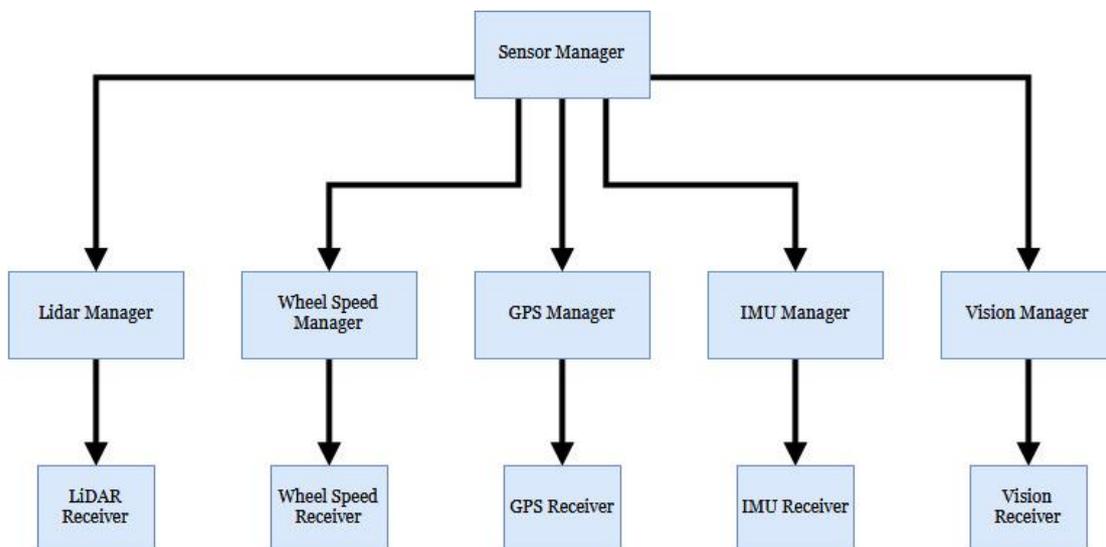


Figure 7: Sensor Manager class ownership structure.

Tier 2 – Mapper and Visualiser

The Mapper receives object information including positions and dimensions of the car, physical objects and waypoints with reference to the starting position of the car. The most recent object information is available to the Main class on request. Two data processing classes are utilised to improve the accuracy of the object information that will be discussed in Section 6. The Visualiser displays the object data provided by the Mapper and is discussed in Section 5.

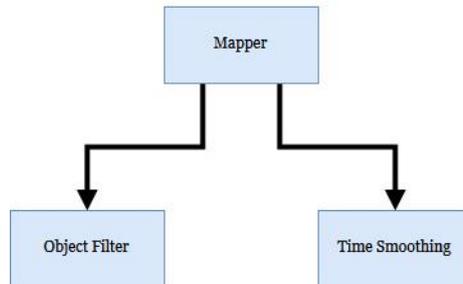


Figure 8: Mapper class ownership

Tier 2 – Path Planner and Controller

The Path Planner receives object data and vehicle position data to produce a series of desired car positions. A mathematical curve is generated by the Baseframe class which the Maneuver class uses to generate potential car positions. The Controller is given these desired positions and outputs instructions to the low level motor controllers. Development of a new controller is under development so the software structure is not yet well defined.

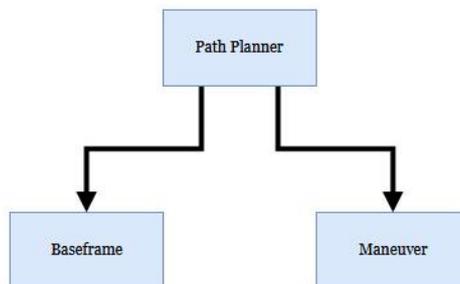


Figure 9: Path Planner class ownership

5 Simulation and Visualisation

To aid in the development of the Mapper, Vision, and Path-Planner a data visualisation and simulation system was designed and implemented on the Autonomous car and made available for personal computers.

5.1 Design Considerations

The Vision and LiDAR object detection, and Mapper output required a visual reference to verify the correlation between the real world and the sensor's interpretations. The visualiser has the following requirements:

- Display the objects provided by the mapper.
- Limit the impact on the performance of the control software.
- Be runnable on personal computers.
- Run in parallel to the control software.

5.2 Design Process

SDL2 [16] Simple DirectMedia Layer version 2 was chosen as the graphics platform due to it being lightweight, performance focussed C++ library; limiting the impact on the performance of the software without requiring incorporating a new programming language to the system.

The viewing window was programmed to run separately to the control program and can scale to fit the screen installed on the vehicle or any computers it is run on.

5.3 Simulation

During the project there were multiple periods during which the car could not be driven due to hardware upgrades and bug fixes. To decouple the testing of software with the state of the hardware a basic simulator was developed. The data acquisition systems were designed to store data in a format that allows them to be replayed through the software. Once the data acquisition was successfully implemented functions were built to feed the data back through the software at a scalable rate to enable performance testing.

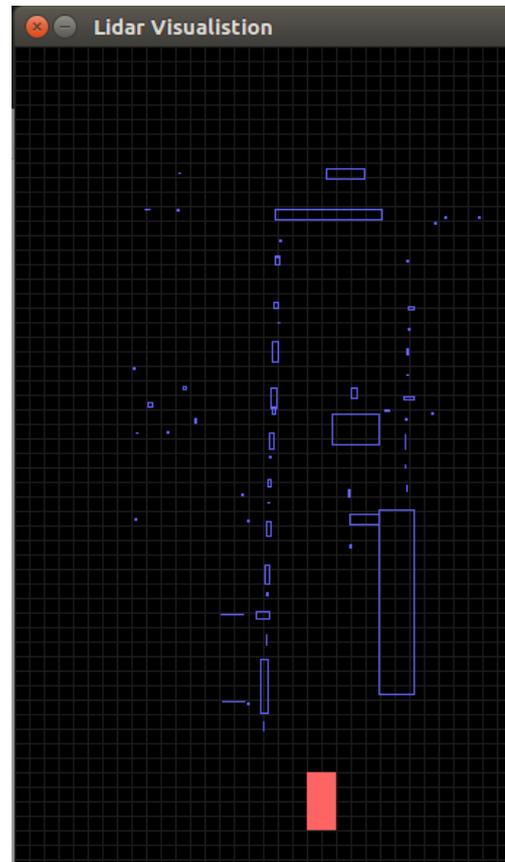


Figure 10: Object Visualiser window displaying objects detected by the LiDAR

6 Object Detection

Two approaches were considered for the detection of cones using the LiDAR. Raw data processing using an extension of the existing road-edge detection algorithm and filtration of the LiDAR object data.

The road-edge detection algorithm discussed in Section 3.2.1 could be extended to find cones placed on bitumen as the disruption of linearity in horizontal depth measurements when encountering a road edge are mathematically similar to that of a cone. However the algorithm is built to find only 2 road edges and would need considerable alteration and testing to deduce the accuracy and reliability of cone detection.

The second method; using the LiDAR's internal object detection, whilst not as open to alteration, would likely be more reliable. This method was chosen as an initial option as it could be tested for reliability sooner than a new algorithm could be developed.

6.1 Data Acquisition with Boost::ASIO

The existing program for receiving LiDAR data had drawbacks that made replacing it a more desirable option than altering the existing code. The data interpretation process was heavily integrated into the control program which made it impossible to receive LiDAR data without the entire control software running successfully; a process that required the other sensors and network of the car to initialise successfully. The data acquisition was also implemented synchronously so the control program would wait for the data to be interpreted when it was requested.

A replacement LiDAR receiver program was developed using the Boost::ASIO C++ library [17]. Boost::ASIO is an asynchronous input/output library designed to manage data input and output in its own thread. Boost was chosen as the software already incorporates the Boost libraries and it is platform independent meaning that it would run on the Raspberry Pi 3, the Jetson TX1 and most computers that may be used in the future.

6.2 Serialisation with Protobuf

The LiDAR produces a large amount of data which must be stored both in the runtime memory of the software and on the on-board hard-drive for simulation. Protobuf – a data serialisation library developed by Google [18] was chosen as a container for the LiDAR data as it is language independent, has low memory overhead, and facilitates hard drive storage of information. Once stored, Protobuf objects can be created from the binary files in many programming languages allowing objects to be passed between different languages.

7 Mapping

The object data supplied by the LiDAR are given with positions relative to the car which is useful for potential collision detection but not for the path planning methods discussed in Section 3.4.1. The control system requires that an accurate representation of the physical world and the car's position within it be available on request. To do this the Mapper class was created to place objects in an absolute reference frame as well as filtering and improving the data.

7.1 Design Process

The Mapper stores its best estimate at the world around it which it improves when it receives new information. This improvement method involves checking each of the new objects with the existing objects for a 'match' and updating the estimate based on the properties of the new object. Two algorithms were developed to achieve this; an object matching algorithm and a time smoothing algorithm.

The design for the Mapper began with an assessment of the LiDAR object position detection accuracy. This was achieved by printing out the object information live as the LiDAR detected large cones (500 mm) placed at known positions with respect to the car. The position accuracy of the cones was found to be within 300 mm at distances of less than 50 m which roughly correlates to the width of the base of the cones.

The ability of the Mapper to correctly match objects is dependent on the accuracy of the LiDAR and the accuracy of the car localisation. As it was assumed that the car localisation would have low error (< 1 m) compared to the gaps between cones (3.5 m minimum [5]) the Mapper's position tolerance could be increased to 1.75 m without introducing false positives in the matching algorithm.

As the odometry was not complete at the time of writing the Mapper was not able to be tested in a live environment. Instead, a session of LiDAR object data was recorded during a drive between cones and used during simulation. As the odometry of the drive was not available the session was video recorded and the cars movement was extracted from the video and emulated in the simulation. The time smoothing parameters were tuned to produce the desired results which are discussed in Section 5.2.3.

7.2 System Design

Object Localisation

The LiDAR provides Cartesian coordinates of the size and position of objects. The localisation uses the latest car position and rotation measurements to transform the coordinates to the absolute reference frame. This is done using the following formulae:

$$d_{c,c \rightarrow o} = \sqrt{y_{c,o}^2 + x_{c,o}^2}$$

$$\theta_{w,c \rightarrow o} = \arctan\left(\frac{x_{c,o}}{y_{c,o}}\right) + \theta_{w,c}$$

$$y_{w,o} = d_{c,o} \cos(\theta_{w,c \rightarrow o}) + y_{w,c}$$

$$x_{w,o} = d_{c,o} \sin(\theta_{w,c \rightarrow o}) + x_{w,c}$$

Where the first subscript denotes the reference frame and the second denotes the object/s.

Note: Angles are measured clockwise from the y-axis.

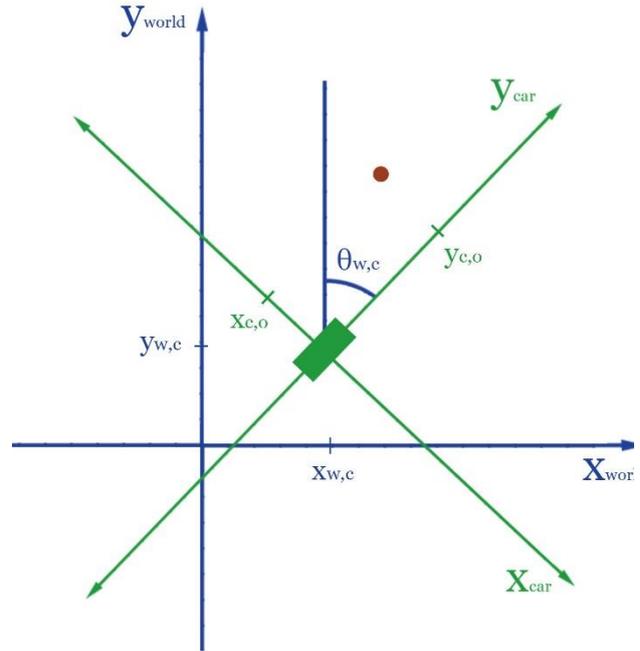


Figure 11: The object (red) detected by the vehicle (green) in the reference frame of the Mapper (blue). The green axis is the reference frame of the car.

Object Filtering

The context of the autonomous drive provides clean data as the flat bitumen environment lacks geometric features other than the cones; however, false positives are still provided by the LiDAR possibly due to dust or marks on the screen or unavoidable noise due to the scattering of light. The object filter works towards providing only object information for relevant objects by rejecting false positives based on distance and size. Objects that are too small or too far away from the car are deleted to reduce processing time and erroneous path planning.

Time Smoothing

During testing of the cone detection it was found that the detection would be missed periodically with the cones flickering in and out of detection even when static. Also, occasionally objects would be briefly detected that had no obvious physical counterpart. Both sets of behaviour are undesired as the Mapper needs to develop a permanent list of the relevant objects in the system. To counter this time-sensitive behaviour the Time Smoother was developed to combine the available data into a more relevant and accurate assessment of the environment.

Each frame of LiDAR data contains each object the LiDAR is currently detecting. After a frame is recorded and filtered the objects are stored in the Time Smoother and assigned an age value, match counter, and a confidence value. For each subsequent frame the detected objects are compared with the existing objects for matches, an object is considered a match if they have dimensions and positions within the tolerances seen below.

Position: The positions of two objects are considered a match if the distance between the two object centres is less than some constant D.

Size: The sizes of two objects are considered a match if the height of the larger object is less than $(1 + S_y)$ times that of the smaller object and the width of the wider object is less than $(1 + S_x)$ times that of the narrower object.

When a match is found a weighted average of the positions and dimensions of the object is found and applied to the object and the confidence value is incremented. If a match is not found the object is added to the system and assigned low confidence. The objects then undergo confidence decay where each confidence value is reduced by a static amount. Objects with confidence reduced to below zero are removed from the system.

Note: the confidence value for objects that lie outside the LiDAR's current detection range are not reduced as the Mapper needs to track cones that it has previously passed.

7.3 Parameter Tuning

The object-match size and position matching values (D , S_x and S_y) can be increased to improve the chance of new objects being paired with an existing object. Increasing these values too high causes objects close together to be misinterpreted as a single object while reducing them too far causes redundancies as new objects are added to the existing list. This has the ongoing effect of slowing down the path planning as it has more objects to calculate that provide little to no benefit to the planner.

The Time-Smoother avoid redundancies and false-positives in object detection by *decaying* the confidence of each object over time and deleting those with zero or lower confidence. The confidence and object deletion algorithm, and the optimal values found through observation are as follows:

```

for (object newObj : new_objects) {
  for (object oldObj : old_objects) {
    if newObj matches an oldObj {
      oldObj.update_size_and_position(newObj);
      oldObj.confidence+= match_conf;
      if oldObj.confidence > conf_limit {
        oldObj.confidence = conf_limit;
      }
      oldObj.match_count++;
      break;
    }
  }
}

for (object oldObj : old_objects) {
  oldObj.confidence-= confidence_decay;
  if oldObj.confidence < 0 {
    delete oldObj;
  }
}

```

Parameter	Value
S_x	0.7
S_y	0.7
D	1.5m
conf_limit	20
confidence_decay	1
match_conf	2

Table 2: Optimal algorithm parameters for time-smoothing

7.4 Results

The car was driven in a straight line through a lane behind the engineering workshops (seen right) to record data for the simulation. After emulating the odometry as discussed above the Mapper was able to deduce the positions of the cones and map its surroundings with success.

The drive provided a total of 464 ‘frames’ of object data. Each frame contains a snapshot of the LiDAR’s observation and can contain any number of objects.

Without filtering or Time-smoothing the Mapper presented the results seen in Figure 13. A total of 3580 objects were discovered over the 464 frames. The filtered results (right) provides a similar level of detail with only 84 objects. This shows a massive reduction in redundant information and confirms the viability of the Mapper as an object provider for the path planner.



Figure 12: The testing environment used during the test recording. The corresponding visualiser output is seen in figure 13.

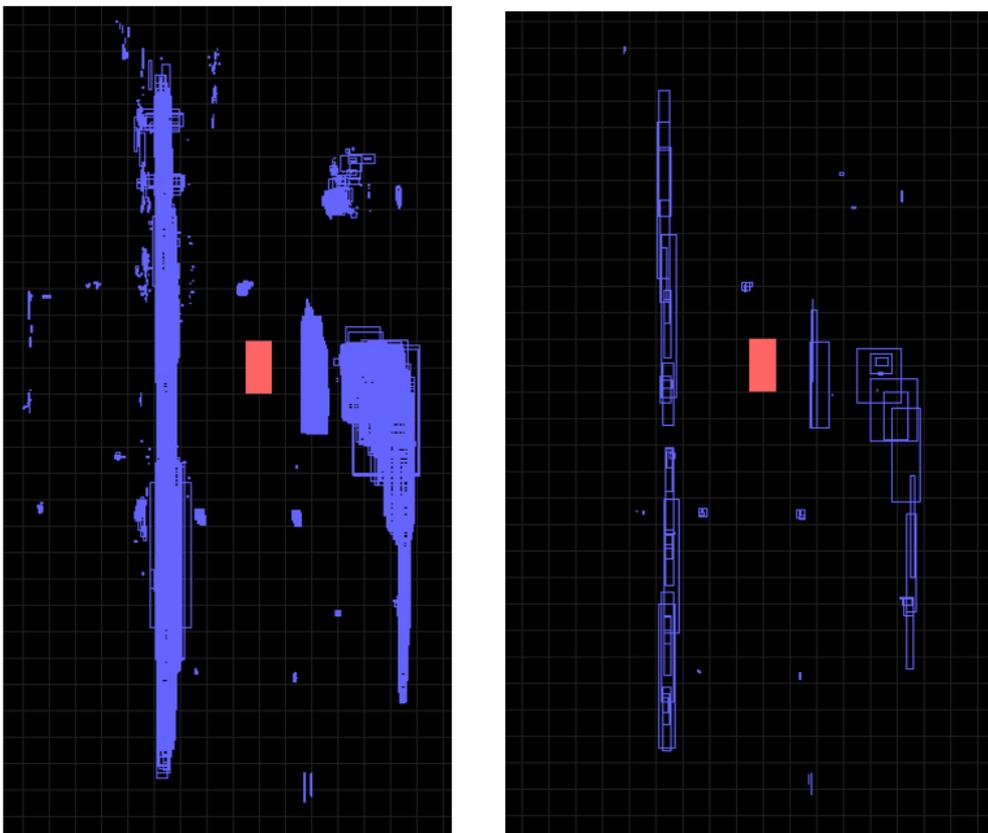


Figure 13: The Mapper output with no object smoothing or deletion (left) compared to the same data set with object smoothing and deletion (right). The red rectangle is the vehicle’s current position.

8 Conclusion

This project demonstrated the successful implementation of an environmental mapper using LiDAR technology with the capabilities of displaying object data from other sources including the cone-detecting computer vision system. The mapper is able to detect and store relevant information from the environment whilst reducing redundancies that would cause performance losses in a live drive. To enable troubleshooting and aid future development a standalone, low-overhead visualiser was programmed and installed on the vehicle to display object data and odometry during both live drives and during simulation on separate systems.

A new control scheme and software system was designed and partially implemented with considerable focus on the ease of future developments on the vehicle. Using sound software engineering paradigms the software was built to enable simultaneous development, testing of subsystems, exchangeability of modules, and expansion of functionality.

9 Future Work

Unfortunately due to the various subsystems being developed in parallel at different rates the software system was not able to be implemented and tested on the car as new developments were made on the pre-existing branch to maintain functional progress on the vehicle. This integration along with testing will be achieved over the following weeks as the team prepares for demonstration.

Beyond the software integration the visualiser will be extended to display the intended manoeuvre and Baseframe of the vehicle to expose the decision making of the system to the observers. The visualisation data will be asynchronously supplied to computers on the network so that the same image feed can be observed outside the vehicle.

Currently the control and visualisation on board the Jetson TX1 are run in serial with the path-planner which could be altered so that all three run on separate threads to reduce blocking due to the processing requirements of each module.

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