CHALMERS
UNIVERSITY OF TECHNOLOGY

Determining sensor-solution enabling future autonomous vehicles

An analysis of sensor vision requirements for detection of obstacles and hazards enabling an autonomous bus docking.

Bachelor's thesis in electrical engineering and mechatronical engineering

KRISTOFFER KRISTIANSSON

DAVID KVIST

Department of Electrical engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

Bachelor's thesis 2018

Determining sensor-solution enabling future autonomous vehicles

An analysis of sensor vision requirements for detection of obstacles and hazards enabling an autonomous bus docking.

Kristoffer Kristiansson
David Kvist

Department of Electrical Engineering
Chalmers University of Technology
Gothenburg, Sweden 2018

Determining sensor-solution enabling future autonomous vehicles
An analysis of sensor vision requirements for detection of obstacles and hazards enabling an autonomous bus docking.
Kristoffer Kristiansson
David Kvist

Supervisor: Jergill, Jonas, Active Safety, Volvo Bussar AB.
Examiner: Ashraf Uz Zaman, Department of E2, Chalmers.

Bachelor's Thesis 2018
Department of Electrical Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: A Volvo 7900-series plug-in hybrid-electric bus departing a bus stop.

Typeset in LaTeX
Gothenburg, Sweden 2018

Abstract

This thesis work has been conducted at Volvo Bussar AB, located at Arendal Gothenburg. The focus has been on determining what kind of sensors and where the sensors should be mounted on an autonomous bus in order to perform a safe bus stop docking.
As part of the pilot-studies for Volvo Bussar AB vehicle autonomy developments this thesis was designed by the authors of this thesis in conjunction with the company. One of the goals was that a new set of eyes on the problem can bring different results.
During the project no hardware realisation of the results have been done, only conceptual results are given. In order to implement conceptual designs, further developments need to be conducted.
The thesis work was put into four parts. Identifying current sensor technology capabilities, finding potential hazards throughout the use-case, applying sensors to these hazards and creating concepts for sensor suites. The use-case given was a bus approaching, docking and departing from a two-lane bus stop. Identifying obstacles and structures.
The environmental factors were limited to sunny and clear weather. If any hazard was located within a sensors field of view, a 100% detection rating was assumed.
Several of these sensor suite concepts were generated and evaluated together with experts from the vehicle safety, sensor and vehicle autonomy branches.
A concept solution was generated but specific sensor-selection was deemed unsatisfactory on a purely theoretical basis and was omitted. The selection of sensors is dependent on proper testing and verification. The sensor-technology is also progressing at a very fast pace. A complete sensor-suite based on specific sensors selected during the thesis work would most likely already be obsolete when implemented on a vehicle due to the high rate of development of automotive sensors.

Keywords: Autonomous drive, Docking, Bus, Sensor-Suite, Concept, Analysis, ADAS, safety.

Acknowledgements

A special dedicated thank you for our supervisor Jonas Jergill at Volvo Bussar AB, not only for making this thesis possible and assigning us it, but also for all your support and guiding.

We also want to thank Anders Pettersson at Volvo Bussar AB for helping us finding and connecting us with our supervisor Jonas Jergill.

We want to thank Hans Magnusson at Continental for the tour of the office and for sharing insight, your knowledge and expertise of automotive sensors.

Last but not least we want thank all our colleagues at Volvo for making us feel welcome at the department.

Kristoffer Kristiansson, David Kvist, Gothenburg, May 2018

Contents

List of Figures

List of Tables

ACC - Autonomous Cruise-control
ADAS - Advanced Driver Assistance System
APS - Automatic Parking System
BOM - Bill of Materials, List of materials, equipment and components for construction of product.
BSD - Blind spot detection
CAS - Crash Avoidance systems
FoV - Field of View, Usually in regards to the arc where a sensor can detect.
FPR - False Positive Rate
SLAM - Simultaneous localisation and mapping
TPR - True Positive Rate

1
Introduction

The introductory chapter of this report will present aim, goals and the topic of this thesis. Background to why this thesis is to be conducted but also the limitations of scope made to achieve a result realistic within current time-constraints.

1.1 Background

The automotive industry is in a rapid development phase where autonomous vehicles are rapidly developed by several companies. All autonomous vehicles require detecting and sensing of the surrounding environment in some fashion.

Choosing sensors for an autonomous vehicle is a sensitive task since there is not a single sensor technology that can accomplish everything. Every sensor-type comes with its own advantages and drawbacks. An autonomous vehicle without enough detection abilities could lead to potentially fatal injuries or accidents.

The development platform and final line-produced vehicles are two different phases of a product and therefore the sensor setup is often not the same. There is no problem to sense and detect objects of interest within the surrounding environment when cost, size, energy use and data processing power are limitless. By implementing all sensors there is a good possibility to achieve some success but this approach by producing a "perfect" vehicle and then scaling down is not the only way.

Why specific sensors are selected for the sensor suite are not always obvious or investigated enough. According to our contact at Volvo Bussar AB and during contact with multiple autonomous vehicle projects at CHARM it is usually down to picking what is available. Volvo Bussar AB wants a different set of eyes looking at the problem from a fresh perspective. This is where the authors and this thesis comes into play.

To enable an autonomous vehicle to function the vehicle must be capable of sensing and mapping the environment. The authors approach to this issue is to first ensure the necessary sensor-data is available in a specific use-case by providing a conceptual sensor-suite. This sensor-suite should be sufficient to provide the autonomous vehicle with data to enable it to function autonomous in a specific use-case. The thesis is limited to a specific use-case partly due to the issues described in `section 1.5` but also since a ground-up approach is possible. By identifying the required data in a small scope, combining this knowledge with several different scopes it is possible to assemble these into a complete sensor-suite.

When talking about autonomous vehicles the needs are different depending on what type of vehicle it is, a regular car has different requirements compared to a bus or a truck. Since this thesis is done for Volvo Bussar AB and the vehicle is a bus and a typical bus specific use-case was chosen.

1.2 Context

During this thesis, the use-case will be investigated in order to find potential hazards and objects of interest (further on OoI) within it. Using the investigation's results, requirements for the final concept solution will be determined. The end result will be a concept consisting of a set of sensors that would enable the autonomous vehicle to perform a docking without posing a risk to surrounding structures, any living creature or vehicles in the vicinity.

1.3 Requirements of solution

By carefully analysing the use-case, the location of objects of interests and potential hazards in relation to the autonomous vehicle will be found. Using these hazards and OoI a set of requirements will be set up for which the final concept needs to fulfil. The goal is to accomplish a safe approach, docking and departure from a bus stop with complete detection of hazards and OoI.

1.4 Questions to answer

Some questions the authors want answered are:

- Are current sensor-technology capable of detecting all the information needed for enabling and autonomous docking at a bus stop?
- Is it a viable method to individually solve the detection of OoI and potential hazards and combine these solutions into a complete solution?
- How are different sensors currently applied in ADAS and can they be applied to the use-case in this thesis?

1.5 Limitations

The following aspects are not considered in this thesis.

- Economic aspects, prices of sensors, cost of implementation
- Computational requirements
- Weather conditions other than clear weather.

Prices of sensors are difficult to find, while manufacturers are sometimes willing to give a broad estimate of what the price of a sensor could be. More often than not sensor prices are often very individual depending who the manufacturer is selling to. In other words, giving a relevant price idea is next to impossible.

Computational requirements are excluded due to the many different variables in play. What algorithms used in object detection, what sensors are used together.

In order to limit the scope and provide fewer factors the weather condition was set to be ideal as suggested by supervisor Jonas Jergill at Volvo Bussar AB.

2
Methods

Methodology and description of how the work will be conducted as described in this chapter. It outlines how the work has been planned.

2.1 Procedure

The project will be conducted in a semi-consecutive order, certain steps depend on previous research or procedures being partially or wholly conducted.

2.1.1 Pilot study

The pilot study will include a quick investigation of currently available automotive sensor-types and technologies relevant to the thesis. Some Advanced driver assistance systems (ADAS) will be investigated in the regard to which sensors and where these sensors are implemented. This is due to the assumption that an autonomous vehicle most likely will be built on the knowledge gained from ADAS currently deployed. Finally, the use-case will be thoroughly investigated and the authors will design a reference bus stop for the use-case.

2.1.2 Identifying objects of interest and Hazards

Hazards have been defined in the context of the scope of situations or areas where damage to vehicles or person can occur. Since an autonomous vehicle must be able to traverse without causing harm or damages, therefore these hazards must all be detected. Which hazards to be considered part of the use-case will be done in conjunction with the supervisor at Volvo Bussar AB but also during the work in connection with the use-case. Finally, a bus stop will be visited, bus-docking observed and photographed. Any new hazards connected with the use-case will be incorporated into final concepts.

In addition to hazards, there are also objects of interest which can be defined as objects or areas to be detected for ensuring proper handling of a vehicle in traffic, this can be in the form but not limited to of traffic signs, lights, stop lines, detecting platform-edge and other non-hazardous situations.

By integrating all the hazards and objects of interest and in turn choosing sensors allowing detection of these, the autonomous docking procedure will be possible assuming the autonomous functionality is available.

2.1.2.1 Weighting objects of interests and hazards

When hazards and objects of interest have been identified and discussed in conjunction with supervisor Jonas Jergill at Volvo Bussar AB, to ensure no important object or potential hazard is omitted, the hazards and objects will be discussed in a workshop. The aim is to ensure complete coverage and determine direction, minimum detection distance and required detection width at the determined distance.

To ensure the study is conducted in a manner where metrics related to OoI or hazards are not omitted the docking procedure will be divided into three phases. These phases will be investigated separately and later combined during the concept generation, where requirement overlap between the phases occur.

2.1.3 Case-concept solution generation

Concepts will be generated, not on a complete basis since the project consists of a pre-study and not a complete product, to combat each individual hazard and properly identify OoI. Hazards possible to cover with several different sensor-suites or solutions will in some cases have several generated concepts. These concept will be summarised in sections 3.7.1 - 3.7.3.

Handling and identifying the OoI and potential hazards individually will greatly simplify generating a concept solutions. A complete system is however necessary, therefore at least one complete concept with several sensors will be proposed in later sections.

2.1.4 Complete vehicle concept generation

A brainstorming session will be hold where the authors of this thesis will try to find a solution to each and every OoI and hazard outlined in section 3.6 in a complete sensor-suite. If a solution is found satisfactory but possible to modify sufficiently to be relevant then this will be added as a variant in the concept.

2.1.5 Evaluating the concepts

The Complete concepts generated in 2.1.4 will be evaluated in conjunction with Volvo Bussar AB, the results of this workshop will be collected and outline in a table, advantages and disadvantages listed. From this workshop, the goal is to generate a final concept or at least select a few options. This workshop will hopefully lead to new useful insights and potentially revelations.

2.1.5.1 Finalised concept from workshop evaluation

Through the discussions at the workshop and evaluation of generated concepts a finalised version is to be generated. This will be our result.

2.1.6 Report-writing

The report-writing is the finalising part of the thesis. This part is especially important since the thesis and generated concept will be used as a foundation for evaluating potential future solutions for vehicles, test-platforms and selection of sensors at Volvo Bus AB and/or subsidiaries.

Relevant information from the pilot study, investigation of use-case, identification of OoI, hazards, pictures and visualisations of generated concepts will be compiled. This will be followed by a discussion with reasoning behind the concepts and finally a conclusion of the project.

2.2 Reliability

The proposed concept will generate a result usable to the company. The goal is not necessarily to create a perfect concept sensor-suite but to contribute to the final product with another point of view. With proper background and pre-study of the use-case, a valid result will be obtained since the authors of this report will be able to observe the problem from a different point of view.

3

Investigations

In the following section, four commonly used sensor-types will be investigated and their features, limits and various properties of a given sensor type presented. This will be referred to later in the concept generation section of the report.

The subchapter 3.6 will discuss and outline issues, potential dangers and objects of interest at a chosen bus stop as well as how these potential dangers and objects of interest affect the selection-process of sensors.

3.1 Radar

Radar, short for Radio Detection and Ranging works by sending out a pulse of electromagnetic energy. This pulse is commonly referred to as a chirp and it reflects off of a struck object and returns to the radar. The reflected pulse is called an echo and is used together with the measured Doppler shift to calculate distance, direction and relative speed of the detected object, relative to the radar.

A radar can be categorised into what type of radar signal is transmitted, for example, CW (continuous wave) or pulse-radar. A commonly chosen type of radar found in modern ADAS today is FMCW (frequency modulated continuous wave radar). Instead of a simple pulse of electromagnetic energy, the FMCW radar sends a radar chirp that is a modulated signal being swept through a band of frequencies. This signal sweep can be done in different fashions to form e.g a sawtooth, a triangle form or using some other algorithm in order to create the chirp waveform.

This report only contains "mm-wave" FMCW radars in the 72-81 GHz frequency range.

3.1.1 Radar types, limits and abilities

When developing a radar certain physical properties has to be taken into consideration. A formula often referred to within radars are the Friis transmission equation.

$$\left(\frac{Pr}{Pt}\right) = \left(\frac{ArAt}{d^2\gamma^2}\right)$$

Pt, Transmitted power
Pr, Received power
Ar, Area of receive antenna
At, Area of transmitting antenna
d, the distance between receive and transmission antennas
γ, the wavelength of the radar

Another important aspect of radar design is the antenna gain, a higher gain increases the distance the transmitted signal travels but it also limits the FoV(increases the directivity of the sent signal) of the radar unit. Basically, detection of objects can be accomplished in a far distance but with a narrow FoV or short distance but wide depending on the gain.

3.1.2 Size and fitting

The mm-wave enables the production of smaller sensors. In comparison, a 24 GHz (12.5 cm-wavelength) radar requires about three times larger aperture to achieve the same performance as a mm-wavelength radar. Using the Continental ARS441 a mm-wavelength radar as an example, the size of the complete sensor modules including connectors is 137 x 91 x 31 mm. [1]

A radar requires a fully propagated signal in order to detect objects, this creates a spot right in front of the sensor where the signal is not yet propagated and is essentially blind and unable to detect anything closer than a couple of centimetres. Electromagnetic waves can penetrate certain materials. This enables the sensor to be mounted behind a (preferably calibrated) fascia, allowing the sensor to be removed from the elements surrounding the outside of the vehicle.

3.1.3 Power consumption

The Continental ARS441 has a rated power consumption of 8 W. [1]

3.1.4 Robustness

The electromagnetic waves ability to penetrate materials allows the radar technology to be fairly robust. Rain or heavy fog shortens the radar's effective range but does not completely inhibit the radar's ability to detect distant objects. The radar's ability to continue operation and detect objects through bad weather is an important reason to consider radar for automotive purposes.

3.1.5 Special restrictions

Due to the correlation between a higher antenna gain and lower FoV, radars are built with different pre-determined specifications in mind. Manufacturers, in turn, classifies their radar units into different classes. These classes are often called SRR (short-range radar), LRR (long-range radar) and MRR (medium range radar). A short-range radar has a shorter range but a wider FoV while a long-range radar has a longer range but a narrower field of view.

Some objects are easier to detect with radar than other. In order for the radar to detect an object, the transmitted power must hit and return back to the radar. Several factors determine how much of the radar signal is received back. Some of these are the objects ability to reflect the signal back, the distance of the object from the sensor and the environment the signal travels in. In essence, an object that absorbs the radar signals instead of reflecting them back is unable to be detected by the radar, a shiny metal surface reflects more radar signal in comparison to a piece of fabric.

Radar cross section or RCS is a measure of how detectable an object is by radar. It's easy to visualise it as a product of three factors.

RCS = Projected cross section × Reflectivity × Directivity

Reflectivity: Not all power transmitted by the radar that hits an object returns. This is due to some power is absorbed, reflectivity is the percent of power hit that gets scattered.

Directivity: A measure of how much of the power scattered off of the object is directed back to the radar. Different shapes reflect different amount of power back to the radar, a flat plane could reflect all of the power back to the radar while a tilted flat plane could reflect all of the power away from the radar.

Choosing the right type of radar for a specific use case is important because there is no single radar unit that can catch all use-cases.

3.2 Lidar

LIDAR is an acronym which stands for “Light detection and ranging”. Fundamentally lidar works upon the principles that focused and intense beams of light can be emitted and the return-reflection of this emitted light can be detected with great accuracy in time. The time-delay between send and receive is then used to calculate the distance to the object reflecting the beam. Similarities between Radar and lidar are many since both are dependent on time-stamping the return-signal/light-reflection. [2]

Radar is handling electromagnetic-waves while lidar is measuring photons (light intensity). The light emitted will be reflected to the detector and this echo will be used to create a 2D-map of dots. Lidar works independently of light-conditions. [3]

By detecting Doppler shifts in the signal the radial velocity can be interpolated from received data.[source citation] A lidar system builds a point cloud, each point is a return of a lidar pulse denoting position (angle) and distance. There can also be data with relative speed to the sensor.

3.2.1 Lidar types, limits and abilities

There are mainly two types of available relevant lidars on the market, mechanical and solid-state lidars.

3.2.1.1 Mechanical lidars

Mechanical uses a rotating housing containing the laser and receiver equipment. This gives good Field of view (further FoV), usually up to 360 °. The Laser emits a collimated (focused) beam as a source and the receiver uses optics to focus the scattered and lower-intensity return.[4] An example of a rotating mechanical lidar-sensor is the Velodyne HDL-64E.[5]

Advantages of the mechanical variant include good FoV (360°) but the unit is fragile, usually quite expensive and bulky. Placement is important, to utilise the entire FoV a quite exposed placement is used such as corners of vehicles or even roof.

The detection range is up to 120 m[6] but varies with the items reflectivity, a black target is harder to detect than a high-visibility paint.

Detection arc is adjustable but 360° rotation combined with a 26.5° vertical detection field is possible. The directivity of the vertical FoV is +2° to -24.5°.

There are also smaller sensors more suitable for line-produced vehicles and not for development and research. These sensors are more compact and the housing is not rotating but the components inside the housing are rotating. Expected performance is similar to the HDL-64E when the same amount of emitters and sensors are used.

(a) Velodyne VLP-16, image not to scale.

(b) Velodyne HDL-64E, image not to scale

Figure 3.1: Two mechanical Lidars

(a) images courtesy of Velodyne Lidar, Inc.

3.2.1.2 Solid-state lidars

Solid-state lidars use an array of light-emitters sending beams of light through a diffusor-lens to form a horizontally wide but vertically narrow beam of light, usually a diode. Each emitter-diode in the array is used for a vertical plane. These planes will be projected in parallel one under the other and usually really narrow. Currently available sensor examples are LeddarTechs LeddarVu8 and Quanergy S3.

The development of solid-state lidars are progressing but products have yet to be widely available. The production of solid-state lidars are however using the same manufacturing techniques as camera-sensors and the laser-diodes can be made on the same substrate, this drives cost down and solid-state lidars are expected to become much cheaper. Even maybe on par with regular vehicle-grade cameras which cost in the neighbourhood of a couple hundred Swedish crowns (a couple of tens of USD).

Disadvantages of currently available solid-state lidars are the limitation in FoV both vertically and horizontally.

The sensor in a solid-state lidar is a planar sensor and can not have a greater FoV than 180° without the use of optics. Due to the currently used wavelenghts, the realistic FoV is however not greater than 180°.

Quanergy S3 have a horizontal and vertical FoV of 120°, theoretically the intensity of the detected objects should be lower with increasing angle due to vignetting of the light, that is to say, the light travels further than light coming straight on the sensor (90°, tangent).

The performance of current solid-state lidars are worse than rotating lidars but also the cost is lower. LeddarTech lidars of the Vu8-series have varying detection ranges from 6 m to almost 200 m.[8] The angles both vertically and horizontally are generally much lower than a mechanical sensor.

3.2.2 Size and fitting

The mechanical lidar HDL-64E have its measurements given in inches and is available in its whitepaper. Metric measurements are approximately 30 x 22.5 x 22.5 cm. There is however, an additional area of 15 x 12 cm needed for cable installation.

The LeddarVu sensors have dimensions varying but an area of 75 x 70 mm should be sufficient for most variants. The sensor can be hidden behind a fascia or windshield.

3.2.3 Data bandwidth

Due to how the data is ordered from a lidar and the systems in an automotive vehicle, usually, want to build an internal map the data usage is fairly high. Larger lidar-sensor and more points lead to higher accuracy but also more data. A higher sample frequency also means more data. According to Velodyne their HDL-64E mechanical lidar has an updating frequency of 15 Hz and generates more than a million data per second.[6].

According to the manual of Velodyne HDL-64E the increase or decrease of updating frequency does not increase bandwidth but instead increases or decreases the vertical angle of the sensor.[7]

The manual states the datarate of a sequence of six firings of all the emitters in the housing to be 12.48 Bytes/µs or approximately 12.5 Megabytes/s or 100 Megabits/s.

3.2.4 Power usage

The LeddarTech Vu8-series sensors consume 2 W typical.
Velodyne HDL-64E draws 48 W typical.

3.2.5 Current usage of lidars

Current lidars are used for SLAM - Simultaneous localisation and mapping. I.E. for mapping environment and not for object detection.

3.2.6 Robustness

Reflectivity: Lidar utilises the returning photons of the emitted beam. This limits the range an object can be detected to the reflectivity of the objects' surface.

A matte or dark object is far less detectable than a reflective white object. However, when observing items such as a traffic sign the contrast in reflectivity is detectable by a lidar and figures and lines can be detected assuming the dot-dispersion is not too high.

Dark does not necessarily constitute the same as dark to the human eye but rather to the wavelenght of the emitted laser-light utilised by the lidar. This is however often very similar since the wavelenght of many lidars such as the Quanergy S3 and Velodyne HDL-64E is 905 nm.

Lidar is however not well suited for glossy or wet surfaces and works poorly for these kinds of surfaces.

Noise: The reflected light is sensed with a CMOS-sensor. The signal is then amplified, signals reflected from a farther distance need higher amplification and this is a variable setting. However, higher amplification means higher noise-levels and false positive rates (further. FPR) may increase and be detrimental to reliability metrics.

Safety: Lidars are a laser product and improper use or deployment can lead to damage to human eyes. However, by limiting duration (duty-cycle) and/or choosing with care the wavelenghts of lidars, damages can be avoided. There are no other health-hazards with lidars. Most lidars use low duration pulses to ensure safety.

Updating frequency: Lidars are variable, a higher updating frequency can be achieved but a lower FoV must then be selected and vice versa. Implementations using rotating lidars must be done with care to ensure that the rotational speed is sufficient for mapping of the environment at the speed the vehicle is going.

3.3 Ultrasonic Sensors

Ultrasonic technology has many applications, non-destructive testing, medicinal diagnostic imaging, some animals even use ultrasound for echolocation. A sound wave with a frequency above the human hearing range is called an ultrasonic sound wave and ultrasonic technology refers to the technology where ultrasound is applied in one way or another.

Ultrasonic sensors use these ultrasonic sound-waves as means for gathering information. This report only contains automotive ultrasound sensors of the single transducer type, where a single component both acts as a speaker and microphone for both sending and receiving ultrasonic signals.

In order to gather information about objects in the sensors vicinity, an ultrasonic chirp is sent out. This chirp can consist of any frequency above human hearing and can be swept through a band of frequencies. By using the speed of sound and the time it takes for the chirp to hit an object and return, the distance between the sensor can be calculated.

3.3.1 Typical Characteristics, features and limits

Ultrasonic sound waves share all the physical properties of sound waves within human hearing ranges, thus the speed of ultrasonic sound is affected by the medium it is travelling in. In order to make an accurate measurement several variables have to be known. These are humidity and air temperature. Otherwise, a measurement fault can occur if the calculations are done using the speed of sound in cold, dry climates but the measurement is actually performed in hot and humid climate.

3.3.1.1 Size and fitting

Ultrasound sensors need to be mounted at about the same height where its supposed to detect obstacles. Typically, the sensors are found to be mounted in bumpers surrounding the vehicle. The size and shape of the sensor is typically a cylinder with a diameter of approximately 25 mm and depth of about 35 mm.

3.3.1.2 Power requirements

Ultrasonic sensors draw up to 6 W depending on model and make. [10]

3.3.1.3 Robustness

An ultrasonic sensor is a fairly simple device, a small disc is vibrated at the chosen frequency. Ultrasonic sensors are robustness and resilience towards the surrounding elements since most ultrasonic sensors are partly exposed to the vehicles surrounding environment. The detection capability of an ultrasonic sensor is both affected by the chosen frequency, size and distance of the object. Depending on the setup a small object could potentially be undetected at a distant range, but up close it is detected. The Bosch 6th generation ultrasonic sensor can detect a 7.5 cm diameter pole as close as to within 15 cm and up to 5.5 m [10]

3.3.1.4 Special restrictions

The ultrasonic sensors found commonly in vehicles today are simple one transducer sensors. As such they send and receive the ultrasonic chirp and echo using the same component. This solution enables no way to determine at what angle the struck object is in reference to the sensor. This limits the information gathered by the sensor to a number of objects in the proximity of the sensor and their distances to the sensor. In essence, it can detect that an object is within the sensors range and the distance to it, just not where it is in relation to the sensor. A common solution for this is to mount several sensors around the vehicle.

Ultrasound is inherently a slow sensor technology compared to other available sensor technologies. This is due to how slow the speed of sound is compared to the speed of electromagnetic radiation. Sound travels through dry air and 20 °C at 343 m/s but light travels at speeds of 299 792 458 m/s. This, in turn, means that the time it takes for an ultrasonic sensor to measure an object(without processing) at five meters away takes at least 29.25 ms but it would take a lidar or a radar 33 ns.

The inherently slow data gathering is part of the reason why ultrasonic technology in vehicles is mostly applied to less time critical systems such as parking aid systems.

3.4 Cameras and Optical Sensors

This report will mention cameras but as a sensor technology, the technology is not only limited to specifically the cameras but also the accompanying necessary image processing. As humans use sight to judge distance and evaluate if there is an obstacle in front of the vehicle. The cameras as a unit only relay the detected light and no actual evaluation of the image is done. This is where digital image processing comes in.

There are also stereo cameras available as a single unit. There are negligible differences between the complete units and using two single cameras together in conjunction, as long as angle and positioning are adjusted correctly. Stereo cameras have the advantages of using the difference in angle between the cameras to the target to calculate distance. This is done with angular measurement through the parallax method. The same calculations can be done with two identical cameras pointing in the same direction with separation between the cameras.

3.4.1 Fundamentals and technology brief

Since the scope of this report is limited to the sensor's capabilities and not the software implementation, the optical sensors and cameras will be regarded as a unit, a black box, with sufficient computer performance for digital image processing will be assumed available. Currently available optical sensor-suites also tend to be sold in conjunction with software and processing units. Some cameras have limited compute performance integrated with functions including but not limited to error/fault-detection (Dirt/dust/ice on the sensor), road-sign and vehicle license plate detection, lane-detection and more.

3.4.2 Typical Characteristics, features and limits

For the following section, a typical sensor has been selected. Texas Instrument (henceforth TI) has an automotive sensor with a publicly available datasheet and with generic performance with currently deployed sensors. Resolution is 1.3 Megapixel. [12].

3.4.3 Size and fitting

The module from TI is not complete with a housing or optics but circuit board of TIDA-00421 is 20 x 20 mm. A housing, fasteners and optics could be estimated to approximately 25 x 25 x 45 mm. This creates a small footprint, weight is less than 50 grams.

3.4.4 Data bandwidth

Data-rate and bandwidth is something which must be taken into consideration. A camera with colour needs more data than a mono-colour camera. Computations can be done on mono-colour (grey-scale) even if the camera is colour-capable.

Looking at a reference-camera with the resolution of 1.3 Megapixel at 30 Hz. Calculating raw data with 256 levels of saturation and contrast gives each pixel a size of 3 bytes or 24 bits, also called RGB24, if 4:2:0 encoding is used the necessary bandwidth, as well as the vertical resolution, is halved. This encoding is usually done during the recording process by the camera and does not increase the need for computational speed.

When mono-cameras are used only 8 bits data per pixel is used and 4:2:0 encoding is not relevant according to Thomas Ytterberg in a conversation 15th of March, screen expert and editor at Geeks AB.

Table 3.1: Example of bitrates for video-transmission with negligible quality loss

Resolution [Mpixel]	1.3	2.0	3.0	5.0	8.0
Mono-Colour bitrate [Mbps] (uncompressed)	10.4	16	24	40	64
RGB bitrate [Mbps] (uncompressed)	41.6	64	96	160	256
RGB bitrate [Mbps] 4:2:0-Encoding	20.8	32	48	80	128
H.264 Mono-Colour Bitrate [Mbps]	1.3	2	3	5	8
H.264 RGB Bitrate [Mbps]	4	8	12	20	40

3.4.5 Power usage

Power-draw of the system most likely will not be solely limited to cameras but also necessary processing. This is outside of this thesis scope but should be mentioned. The sensors used it ADAS, back-up or surround view-systems such as the previously mentioned TI-camera typically consumes less than one watt of power.

3.4.6 Robustness

Modern cameras are constructed using CMOS-sensors, these sensors are solid state and not very sensitive to vibrations. The optics are however not as robust but there are widely available automotive cameras in use as of writing.

Since the cameras rely on light and contrast to differentiate between different objects there must be some light present. Modern cameras have good light sensitivity and have a wider span of dynamic range than human eyes according to our contact at an equipment manufacturer of automotive sensors.

The nature of optical sensors means the housing and lens must be kept clean to function. If covered by dirt or debris the sensor fails. There are systems with de-icing capabilities of lens housings, possibilities to rinse off debris with jets of window cleaner fluid and systems capable of detecting if the sensor is covered.

3.4.7 Special restrictions

Lens vignetting is a physical phenomenon where the outlying boundary of a sensor receives less light. This is a direct effect of light travelling through a circular lens and perceived by a flat sensor (CMOS-sensor). Several reasons exist why, firstly the angle of incident decreases further from the centre of the lens, the travelled length of light is farther which in turn decreases the intensity. Finally, since the light travels through the centre of the lens, a circular lens is perceived as more elliptical viewed off centre than from the centre of the sensor.

Correction of vignetting is fairly easy to do in real-time with limited processing power.

Perception distortion is in a similar way a physical phenomenon and restriction of optical image captures. Distortions most relevant, to this thesis and implementations on vehicles, is wide-angle distortions where close objects tend to be exaggerated in size and items further away look smaller. Also, note that distances between close and distant objects are perceived to be further away than they actually are. This means that relative distances between two distant object cannot be discerned properly.

FoV of cameras is a fixed value. Smaller angle means more data per area within the captured video, it also means fewer distortions. Available optics vary but equipment manufacturer Continental has cameras capable of FoV between 65° and 195° of vision.

3.4.8 Distinguished test and theses

Traffic-sign recognition is an example of cameras being used in currently available vehicles. The data-processing should not be too heavy since there have been successful tests by using a smartphone platform.

> *“Finally, a prototype of the proposed system is implemented on a Samsung Note 3 smartphone. To achieve a real-time computational performance of the proposed K-ELM, a CPU-GPU fusion-based approach is adopted to accelerate the execution. The experimental results on different road environments show that the proposed system can recognize traffic lights accurately and rapidly.”* - Liu, W. et al (2017). Real-Time Traffic Light Recognition Based on Smartphone Platforms.[11]

According to the test and quote, there should be amble supply of capable hardware to handle the load of image-recognition.

Another implementation is the "inside-out" tracking of the Windows Mixed Reality headset. The headgear utilises two cameras to calculate the position and direction the user is looking to within a couple of centimetres. The headgear is powered with a single USB-connection and is hence limited to 2.5 W of power. This is sufficient to drive both the two cameras but also the two displays. The computational power for tracking is however not included in these numbers.

3.5 Applied sensors in current automotive industries

In this section a brief explanation of a couple of modern ADAS, what they accomplish and how sensors are used within these systems.

An overview is given of what kind of sensors can be found in different ADAS. Specific variants have been omitted and several automatic parking systems are summarised in the table.

Table 3.2: Typical sensor-usage in some current ADAS

	ACC	APS	BSD	CAS
Lidar	X	X		X
Optical	X	X		X
Radar	X		X	X
Ultrasonic		X		X

As seen in the above table 3.2, some sensor is more suitable for some systems than others. For example, in ACC system's detecting-range and speed is important and ultrasonic sensor's lack of range and slow detection makes these unsuitable in an ACC system, but a stereo optical camera setup, lidar or radar can accomplish this.

3.5.1 Adaptive Cruise Control (ACC)

A regular cruise control is a system that maintains a speed chosen by the driver. It is essentially a system that checks how far off from the chosen speed is the vehicle moving in and uses this difference to determine the amount of engine throttle to apply.

An adaptive cruise control is a more advanced system where not only speed is monitored but the distance to the vehicle in front as well. This allows the system to adapt its speed depending on the current traffic situation. Where a normal cruise control system without intervention would allow the car to collide the car in front of it, adaptive cruise control would prevent this by either warning the driver or lower its speed in order to avoid a collision.

Sensor usage: Different vehicle manufacturers implement ACC using different sensors. Essentially what ACC requires more than the regular cruise control is the ability to determine the distance and relative speed of the vehicle in front. This can be accomplished in many ways but radar is common amongst ACC implementation, but lidar and stereo cameras could work as well.

3.5.2 Automatic Parking System (APS)

The amount of automation varies between manufacturers, but APS is essentially a system that either partly automates parking or it completely automates it. An example of a partly automated parking system would be one that would allow the driver to drive past a parking space and the car will provide the driver with a prompt of initiating automatic and autonomous parking in the parking space.

Sensor usage: Accomplishing an automated parking system requires a lot of processing and sensors. While a system using only ultrasonic sensors could orient the vehicle next to another car, finding and parking correctly inside a parking space on an empty parking lot would be most likely impossible.

Camera, lidar, radar and ultrasonic sensors can be used in conjunction to create an automated or autonomous parking system.

3.5.3 Blind spot detection (BSD)

In a regular car, there are a couple of blind spots where the driver cant sees other vehicles. Drivers overcome this by turning their heads or use their intuition. BSD is a system that gives a warning to the driver if there is another vehicle within the blind spots.

Sensor usage: Theoretically, this can be accomplished using lidar, cameras, ultrasonic sensors and radars. However, commercial systems typically use radars located in the side-view mirrors to detect vehicles.

3.5.4 Collision avoidance system (CAS)

A system that allows the car to detect a potential collision and avoid the collision by steering the car and/or decelerating by actively applying brake force.

Sensor usage: CAS is not limited to a single speed but a wide range of speeds. This means selection of a single sensor type is unlikely but rather a combination of sensors is used. Most importantly is the capability of detecting an incoming collision hazard and take action accordingly. At high speed, a radar is the best candidate while an ultrasonic sensor would have a higher FoV and could be implemented at low speeds where the short range is not detrimental. Cameras can however not really determine speed nor distance reliable enough. A radar suite positioned in the front of the vehicle complimented with ultrasonic sensors around the front bumper is a solution. The system could also potentially utilise the sensors in 3.5.3 located in the side-view mirrors as well other ADAS sensors.

3.6 Use-Case

In the following section, the use-case will be explored in detail. This entails layout of chosen reference bus stop, vehicle, the wanted and expected behaviour of the vehicle. An analysis of potential hazards and sensor requirements to detect OoI involved will also be explored.

Since the scope can be very broad if not properly limited some exclusions have been made and will not be investigated. Some functionality will be assumed to be available. These exclusions and functions will be outlined in subsection 3.6.4.

3.6.1 Overview

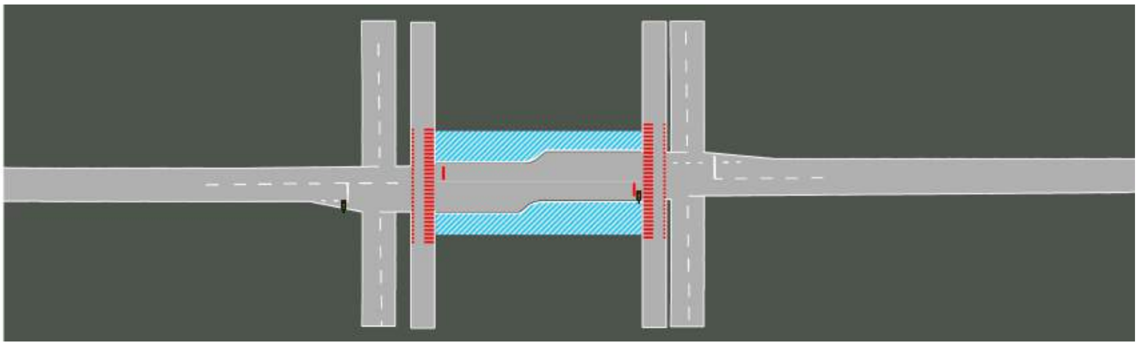

Figure 3.3: Schematic overview of use-case bus stop.

The use-case chosen for this report is an autonomous bus in a "docking" situation. A bus approaches, makes its way to the assigned docking position and stops, then in turn departs. All done in the spirit of safety for surrounding people and vehicles as well as the comfort of passengers.

A two-lane bus stop where the bus docks at the first "docking station" has been chosen, a stop that could be considered a ’catch all’ type of stop involving many features like traffic signals, pedestrian crossings, bike lanes and even crossing traffic.

Figure showing an overview of the use-case bus stop refer to page

3.6.2 Autonomous vehicle overview

The proposed vehicle pictured in the specified use-case in this thesis is a fully autonomous vehicle classified as a fully autonomous vehicle, meaning no human driver or human intervention is needed for full functionality or in case of unexpected events. The proposed concepts should be applicable to more limited semi-autonomous vehicles. Enabling these to assist during docking or semi-autonomously operate in a limited fashion such as when docking the vehicles at a vehicle depot.

Due to environmental benefits and restrictions on emissions such as the EURO 6-emission standard, there are good reasons to assume a future potential vehicle is partially electric (hybrid) or fully electrically propelled. An electric vehicle has interesting properties in regards to acceleration and deceleration where the torque is almost linear from standing still to full operational speed. This makes some of the calculations and assumptions of how the vehicle is conducted in traffic easier and more reliable.

The inspiration for the chosen vehicle within this thesis has been taken from the current generation Volvo intercity bus lineup, Volvo 7900 Hybrid, full electric and hybrid electric vehicle. The 7900-series is available in both 2-axle configuration (12 m length) or as articulated (18 m length). Since the articulated variant adds a level of complexity and lowers the reliability of the case-study the shorter non-articulated bus-size is chosen as the subject of this thesis. Most of the concepts should be applicable, with small complements to the sensor-suite, to the longer 18 m vehicle as well. Early studies done at Volvo Bussar AB has shown that the highest deceleration possible while still maintaining a high passenger comfort is less than $1\,m/s^2$. The maximum possible deceleration with the vehicle is a bit less than $7\,m/s^2$, this level of deceleration is not however without risk to unfastened passenger and injuries are to be expected. A powerful deceleration due to obstacles should be limited to somewhere between these two numbers to ensure safety to the passengers on-board. Deceleration figures of $1\,m/s^2$ and $3\,m/s^2$ has been chosen when calculating or estimating stopping distances and safety margins. The last deceleration figure of $6\,m/s^2$ is limited to the direst of situations to evade a catastrophic accident and is not subject to our study where the goal is to avoid getting in such a situation. The placements of the two axles on the vehicle create overhangs both in front and rear of the vehicle. These overhangs in combination with front axle turning(instead of both front and rear axles) create a situation where due to the fact that the overhang is outside of the wheelbase, it may hit a vehicle, pedestrian or object in an adjacent lane or on top of the bus station platform. In short, the vehicle have a slightly larger zone of occupancy than the turning radius of the wheelbase.

Since the vehicle is pictured as a fully autonomous vehicle some margin of safety must be present around the vehicle. Due to this necessity, a concept called free space is introduced. Freespace as a concept can be defined as an area around the vehicle where any object or being is found within this area a reaction is required.

Free space is situation dependent metric and depends on several factors, the biggest factor is the intent of the autonomous vehicle. If the autonomous vehicle is about to change lane, the free space area would be determined to be the space in the adjacent lane as well as in front of the vehicle, in order to not hit another vehicle or person in front of the vehicle but also not to hit a vehicle in the occupying or entering the adjacent lane. Another factor is speed, the longer it takes for the bus to slow down to a stop in order to prevent collisions, the farther the free space area in front of the bus is required to reach.

3.6.3 Bus stop overview

The bus stop chosen gets its inspiration from a real-life bus stop called *Regnbågsgatan* in Gothenburg, Sweden. It was chosen due to its many features and in order to anchor this report into a potentially real situation for an autonomous vehicle.

The bus stop is preceded by a traffic light and road for crossing vehicles. The traffic light does not indicate whether the bus stop is free or occupied by other vehicles the traffic-lane leading to the bus stop is however limited to buses only.

Right after the crossing road, there is a pedestrian crossing with a bicycle lane. The first docking bay/slot is slightly of kilter from incoming road direction and the docking vehicle must slightly turn into the bay ensuring enough free space for vehicles behind to get into the second and further forward docking bay.

(a) Slabs parallel to edge. **(b)** Curb parallel to platform.

Figure 3.4: Curb and slabs along curb at docking bay

The bus stop consists of two bays for buses and has a raised platform for passengers. The edge to the platform from the road surface is sharp and constructed out of stone slabs with a differing colour to the road surface and passenger platform.

Following the bus stop is another monitored pedestrian crossing with accompanying traffic light and a roundabout which the bus-lane goes straight through. Since both crossings of the roundabout and the pedestrian crossing are synchronised with traffic lights the road-crossing can be considered a single intersection.

The bus stop has several areas where sensory perception is needed in order to guarantee a safe docking procedure.

3.6.4 Exclusions, limitations and assumptions in Use-case

Only the use-case described in scope will be regarded. Only tech and sensors available on the market will be included in the analysis.

The analysis will not investigate what other systems of the bus will be affected. The

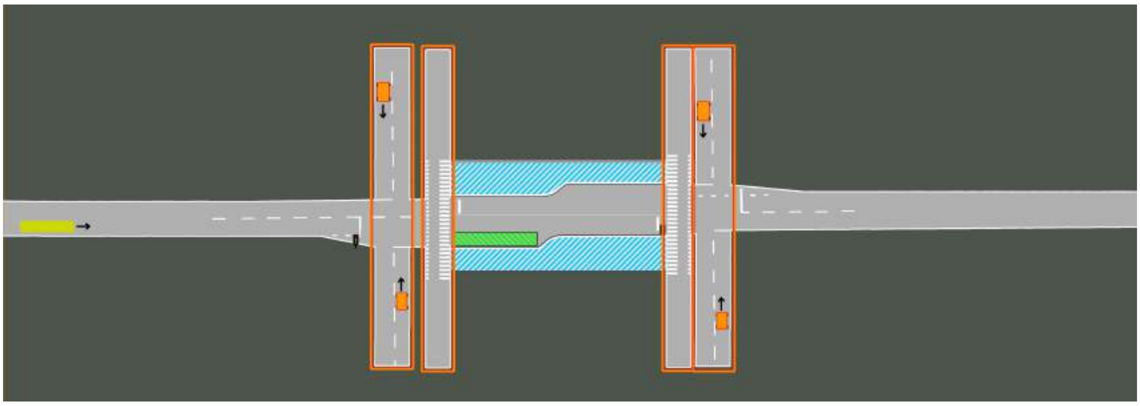

Figure 3.5: Top-down view of use-case bus stop.

(a) Legend:
Yellow Square: The autonomous bus.
Orange: Hazardous areas, crossing traffic, pedestrian walkways and crossing bike lanes.
Cyan: Bus stop pedestrian area.
Green: Bus docking area.

sensor-suite will be regarded as a stand-alone system as far as possible. Environmental specific parameters of the described use-case are not included in the analysis, such as different weather conditions.

If any hazard is located within the sensors field of view a 100% detection rating is assumed.

3.6.5 Phases of an autonomous bus docking

In order to achieve an easier understanding of the needed autonomous vehicle's behaviour for the duration of the use case the vehicle's behaviour is divided into three phases, all of them have a variety of sensor perception needs as well as potential hazards.

As stated in subsection 2.1.2 on page 5 a hazard can be defined as a situation, moment or task where there is the chance of damage or injuries to passengers, vehicles, property or persons.

3.6.5.1 Phase 1: Approach

The autonomous vehicle enters into the use-case at an initial speed of 50 km/h. Due to safety-margins, the vehicle is to approach and stop at the preceding traffic light and intersection before entering the bus stop at a slow speed. This makes it only necessary for the vehicle to distinguish the intersection and traffic light initially.

Figure 3.7: Approach into bus stop from vehicle perspective with a OoI marked.

(a) Legend:
Blue box: The bus stop docking bay.
Red: Pedestrian walkways and bike lanes.
Yellow: Traffic sign and traffic lights

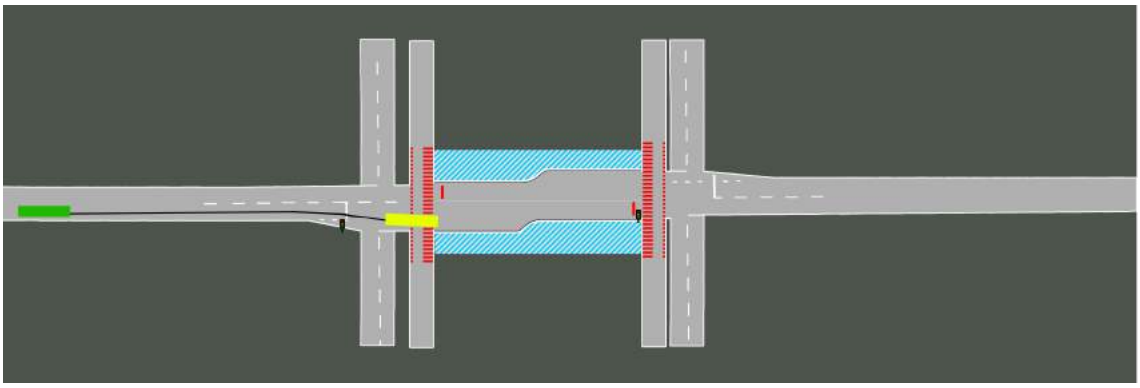

Figure 3.9: Approach-phase start (green) and stop (yellow) position of autonomous vehicle.

At the traffic light, the bus will then progress to the bus stop only if the traffic light permits and the docking bay is clear from other vehicles. The vehicle must have a wide enough angle on sensors to detect any crossing pedestrians or bicycles at the preceding approach, this limits the maximum speed of the vehicle as well.

The docking vehicle will at this stage steer towards the docking bay before the next stage takes hold.

3.6.5.1.1 Phase 1: Hazards and objects of interest As outlined the vehicle approaches an intercity bus stop at a speed of 50 km/h. This should be done in a comfortable manner to the passengers and thus is limited to approximately $1\,m/s^2$ breaking.

The breaking power $1\,m/s^2$ makes it paramount that the vehicle is able to detect the traffic signs identifying a stop in excess of the braking distance of just less than 100 [m]s.

Before the intersection and bus stop, there is a traffic light, signalling the bus to proceed or stop, accompanied by a stop-line. These are objects of interest and a potential hazard can occur if misinterpreted or missed completely. By detecting both traffic light and stop-line true positive rate of detection can be increased when cross-referencing both objects.

There is an intersection and accompanying monitored pedestrian crossing preceding the bus-stop. These both need to be detected to avoid collision with a crossing vehicle or running over crossing bicyclists and pedestrians.

The docking bay may be occupied even if traffic light signals the autonomous vehicle to proceed. If the autonomous vehicle proceeds but docking bay is occupied the autonomous vehicle will stop in the intersection blocking traffic and in a potentially dangerous position. The docking bay and potential occupancy, as well as the intent of occupying vehicle in the docking bay, should be detectable by the autonomous vehicle.

3.6.5.1.2 Phase 1: Sensory requirements At speeds of 50 km/h a collision with a pedestrian or an oncoming vehicle could potentially be fatal, therefore it is only natural to assume we need a longer perception range in order to detect potential collisions and slow down early enough to avoid it or at the very least, limit the severity of the crash.

The identification of traffic lights, crossing vehicles or about to cross an intersection, the FoV needed is narrower further away but widens with the shorter distance to the vehicle.

Early studies done at Volvo Bussar AB has shown that the highest deceleration possible while still maintaining a high passenger comfort is less than $1\,m/s^2$. An initial velocity of approximately $14\,m/s^2$ and a deceleration of $1\,m/s^2$ means a breaking distance of almost a 100 m this distance is the minimum viewing distance needed in front of the vehicle.

Table 3.3: Sensor requirements during approach

OoI or Hazard	Phase 1				
	Maximum Distance [m]	Minimum Distance [m]	Width	GPS Mappable	Direction
Traffic Lights	150	<1	2 Lanes	No	Front
Traffic Signs	150	<1	2 Lanes	No	Front
Intersection	150	<1	>2 Lanes	Yes	Front
Pedestrian Crossing	150	<1	>2 Lanes	Yes	Front
Overhang	N/A	N/A	N/A	N/A	N/A
Platform	N/A	N/A	N/A	N/A	N/A
Curb	N/A	N/A	N/A	N/A	N/A
Persons	100	<1	>2 Lanes	No	Front
Bicycles	60	<1	>2 Lanes	No	Front
Vehicles	150	<1	>2 Lanes	No	Front
Vehicle turn-signals	N/A	N/A	N/A	N/A	Front
Road Markings	>10	<1	1 Lane	No	Front
Lane-ID	>10	<1	1 Lane	Plausible	Front

3.6.5.2 Phase 2: Docking

Docking phase begins after the bus have entered the bus stop and approaches the bay at a slow pace. The bus is to position itself parallel with the platform and at a short distance from it.

At this phase, the bus needs to come to a complete stop at the bus stop, after the docking is complete and the bus is ready to leave, this phase ends.

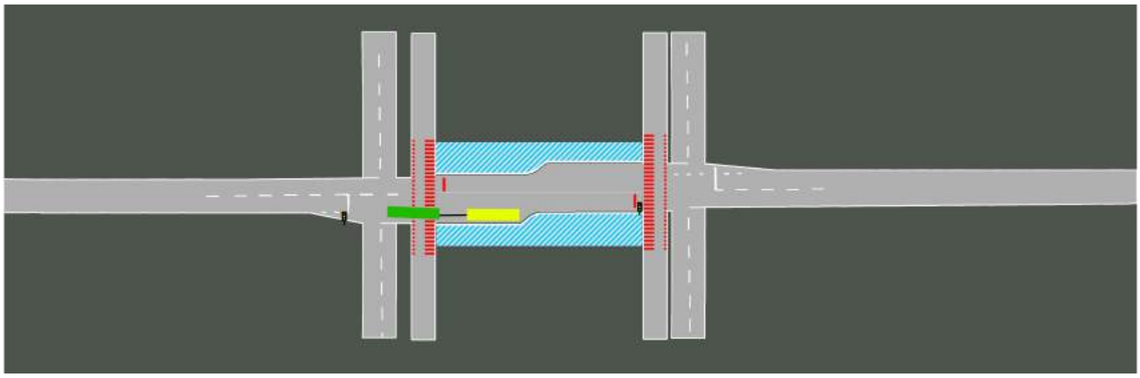

Figure 3.10: Docking-phase start (green) and stop (yellow) position of autonomous vehicle.

3.6.5.2.1 Phase 2: Hazards and objects of interest The docking vehicle must be able to detect if docking bay is clear even if it was deemed clear in the previous phase.

Docking takes place in a docking bay where the passenger platform is slightly raised approximately a 10 cm with a curb of a different colour. Where to traverse and free space is needed, the curb and platform need to be individually detectable and classified correctly.

Correctly identifying the **curb and platform** is part of the path-finding and classifying process of free space where the vehicle can traverse. The autonomous vehicle needs to be able to distinguish between persons on the platform, which is a safe situation, and when there is an obstacle on within the free space area of the vehicle.

Due to the positioning of the front axle, there is a small but potential risk of hitting persons on the platform with the **overhang** in the front of the vehicle when an aggressive turn is made into the docking position.

Persons: Persons on the platform might not see the vehicle and walk into the path of the docking vehicle at the pedestrian crossing or out in designated docking bay. Their intent or at least heading and velocity need to be detected to satisfy safety requirements and ensure safe deceleration.

Curb and platform: If the curb and platform is not properly detected a risk of the vehicle colliding with the curb or run up onto the platform with resulting damage to person or vehicle. Platform and Curb need to be detected if proper positioning is to be achieved by docking vehicle for safe and easy mount/dismounting of passengers.

Vehicles and path-finding: A vehicle might not been detected in the previous phase or incorrectly been identified. In-case of reclassification of the path, occupied by another vehicle, the docking vehicle must be brought to a safe stop with good margins of safety to other vehicles but also passengers.

3.6.5.2.2 Phase 2: Sensory requirements For sensory requirement see table 3.4.

3.6.5.3 Phase 3: Departure

Departures are undertaken at low speed, this limits injuries in case of accidents but also lowers the risk of persons and vehicles in the vicinity to miss the autonomous vehicle's intent of departing the bus stop.

During the departure phase, the bus will first determine a path away from the parked position. This path needs to be clear of obstacles upon initiation but it will also need to be clear for the duration the bus is traversing its path. It is therefore important to determine whether or not any rear approaching vehicle will cause a potential collision with the bus while it follows its chosen path.

The path will first cross a pedestrian and bicycle crossing, then a traffic intersection and continue onward out of the scope of the use-case. Along with this path, there are traffic lights as well as accompanying road markings.

Table 3.4: Sensor requirements during docking

OoI or Hazard	Phase 2				
	Maximum Distance [m]	Minimum Distance [m]	Width	GPS Mappable	Direction
Traffic Lights	N/A	N/A	N/A	N/A	N/A
Traffic Signs	N/A	N/A	N/A	N/A	N/A
Intersection	N/A	N/A	N/A	N/A	N/A
Pedestrian Crossing	N/A	N/A	N/A	N/A	N/A
Overhang	2	<.1	Zone	No	Zone Front overhang
Platform	10	<0.1	Zone	Yes	Zone
Curb	20	<0.1	Zone	No	Zone 180° side
Persons	10	<0.1	Zone	No	Zone 270° Front & Sides
Bicycles	10	<0.1	Zone	No	Zone 270° Front & Sides
Vehicles	20	1	2 Lanes	No	Front
Vehicle turn-signals	20	1	2 Lanes	No	Front
Road Markings	5	<0.1	2 Lanes	No	Front
Lane-ID	10	<0.1	2 Lanes	No	270° Front & Sides

3.6.5.3.1 Phase 3: Hazards and objects of interest The vehicle must detect objects within its determined path.

Both pedestrians and bicyclists may cross the chosen path. Bicycles are faster than pedestrians and while detecting both is important, bikes need to be detected earlier. Pedestrians on the outer lane from the autonomous vehicle can be injured if the departing autonomous vehicle does not detect them. Hence detection on both sides is important. A bicyclist might use the bus-lane and overtake the autonomous vehicle docked to the platform.

Other vehicles crossing at the intersection requires detection to avoid collisions.

Due to the length and location of the rear axle of the bus, when taking a sharp turn the part of the bus that is behind the rear axle (commonly referred to as overhang) can overshoot and come up over and on to the platform. Before departing, checking if this area is clear is important.

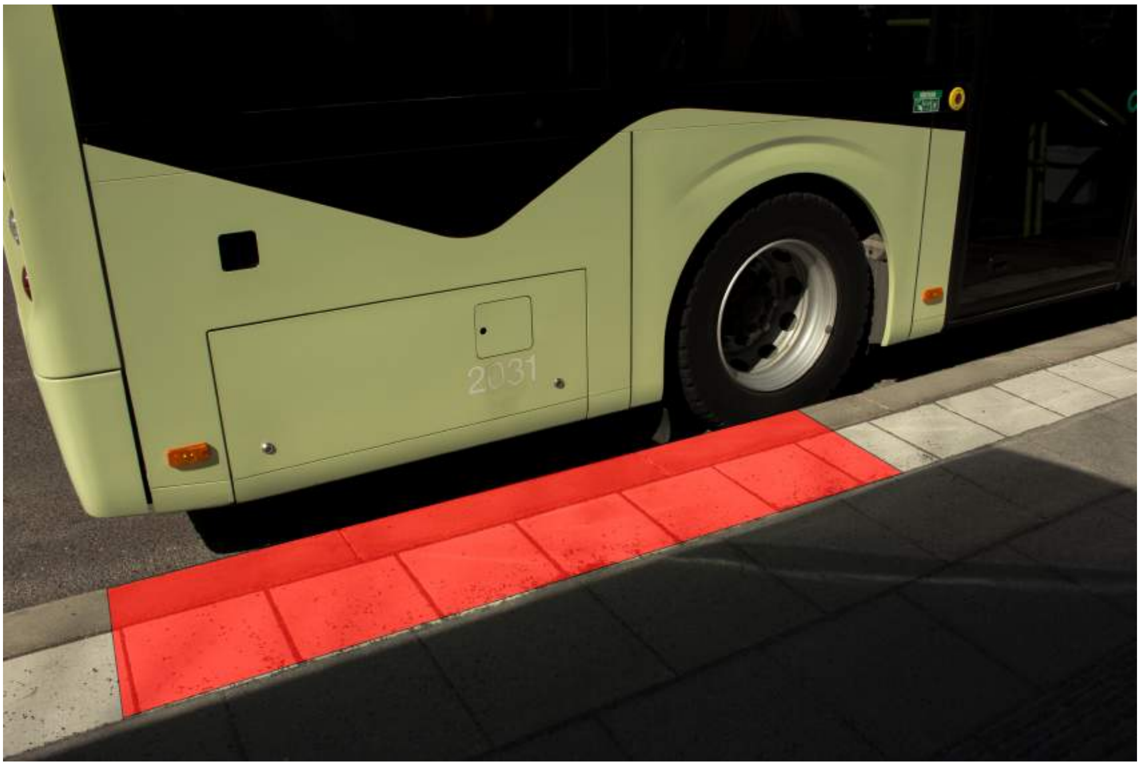

Figure 3.11: Potential overhang hazard outlined in red.

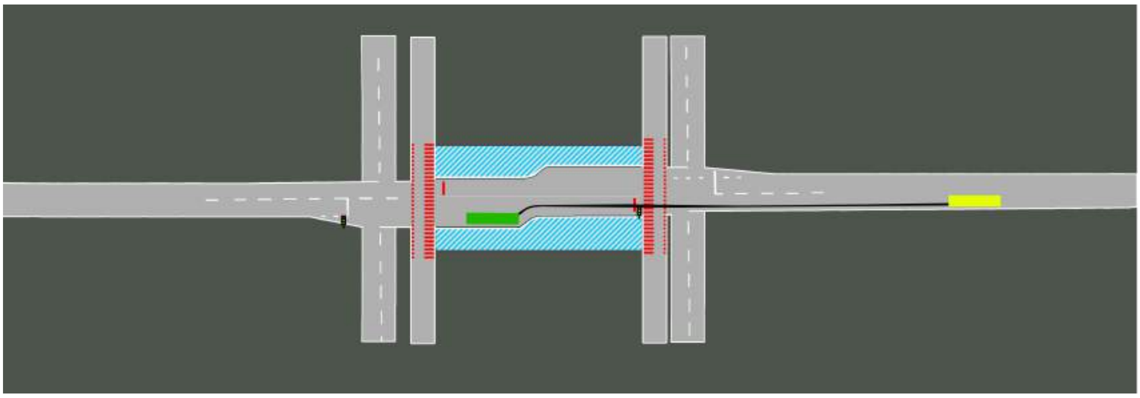

Figure 3.12: Departure-phase start (green) and stop (yellow) position of autonomous vehicle.

Before exiting the bus stop area a traffic lights instruction needs to be detected in order for the bus to follow traffic laws and avoid the potential risk of vehicular collisions.

3.6.5.3.2 Phase 3: Sensory requirements For sensory requirement see table 3.5.

Table 3.5: Sensor requirements during departure

OoI or Hazards	Phase 3				
	Maximum Distance [m]	Minimum Distance [m]	Width	GPS Mappable	Direction
Traffic Lights	30	<1	2 Lanes	No	Front
Traffic Signs	30	<1	2 Lanes	No	Front
Intersection	30	<1	>2 Lanes	No	Front
Pedestrian Crossing	30	<1	>2 Lanes	No	Front >180°
Overhang	2	<.1	Zone	No	Zone Rear overhang
Platform	10	<0.1	Zone	Yes	Zone
Curb	20	<0.1	Zone	No	Zone 180° side
Persons	30	<0.1	Zone	No	Front & Adjacent Lane Pedestrian Crossing 270°
Bicycles	30	<0.1	Zone	No	Front & Rear Adjacent Lane Pedestrian Crossing 360°
Vehicles	30	1	2 Lanes	No	Front & Rear Adjacent Lane 270°
Vehicle turn-signals	30	1	2 Lanes	No	Front
Road Markings	15	<0.1	2 Lanes	No	Front
Lane-ID	15	<0.1	2 Lanes	No	Front & Rear, Adjacent Lane 270°

3.6.6 Identified objects of interests and hazards in use-case

By identifying OoI and potential hazards in previous subsections and cross-referencing the phases there are several duplicates that can be handled as a single instance to be solved or given a concept solution.

As the table 3.6 states there are clearly some sensors more favoured than others such as the Ultrasonic-sensor clearly not capable of identifying or properly detecting some OoI. The necessary detection-ranges varies but by incorporating the worst-case range necessary a single sensor-solution might be used for the entire range.

Table 3.6: Objects of interest and potential hazards with possible solutions and occurrences

OoI or Hazard	Phases			Possible solutions			
	Phase 1	Phase 2	Phase 3	Optical	Lidar	Radar	Ultrasonic
Traffic Lights	Yes	No	Yes	Yes	Plausible	No	No
Traffic Signs	Yes	No	Yes	Yes	No	No	No
Intersection	Yes	No	Yes	Yes	Yes	No	No
Pedestrian Crossing	Yes	No	Yes	Yes	No	No	No
Overhang	No	Yes	Yes	Yes	Yes	Yes	Yes
Platform	No	Yes	Yes	Yes	Yes	Yes	No
Curb	No	Yes	Yes	Yes	Yes	Yes	Plausible
Persons	Yes	Yes	Yes	Yes	Yes	Yes	No
Bicycles	Yes	Yes	Yes	Yes	Yes	Yes	No
Vehicles	Yes	Yes	Yes	Yes	Yes	Yes	No
Vehicle turn-signals	No	Yes	Yes	Yes	No	No	No
Road Markings	Yes	Yes	Yes	Yes	No	No	No
Lane-ID	Yes	Yes	Yes	Yes	No	No	No

Sensors also have different viewing distances and might have blind spots close to the sensor. One example would be optical cameras since the cost of using adjustable optics is high, sensors with a set magnification and FoV is more sensible. This limits the distance between the cameras with a wide FoV can detect a potential hazard or object. As such a combination of overlapping sensors will be needed. The combined data and overlapping areas are stitched together with sensor-fusion.

However not only do a sensor solution need a maximum distance but also close-range detection, there is need to identify the closes an object will be observed from. The most telling example, in the specific use-case studied in this report, would be the traffic lights. During the approach, the traffic light will have to be detected from a distance of several tens of meters while in departure the traffic light might be even closer than a meter to the sensor.

3.7 Solutions to hazards

Handling specific hazards and not general solutions.

3.7.1 Approach Hazards

This subsection will outline some solution proposals with the knowledge and definitions as outlined in previous chapter 3.6.

3.7.1.1 Traffic Lights

The only realistic candidate today is an optical camera, due to the requirement of detecting the traffic signals and not only the housing.

3.7.1.2 Traffic Signs

The detection and presence of traffic signs in itself are possible with both lidar and Radar in addition to optical cameras. Lidars could potentially detect the difference in return signal for different colours on the sign. This is however deemed as non-realistic with currently available sensors to implement.

Radars can detect the shape of the sign but not the content of the sign and has hence been ruled out.

An optical camera with narrow forward-facing FoV has been judged as the candidate with the best chance of meeting requirements set in 3.6.5.1.

3.7.1.3 Intersection

The intersection preceding the bus stop should be detectable not only by itself but also by interpreting other data and reach the conclusion. In essence, the intersection itself poses no real danger unless there is a vehicle in the intersection and a potential collision could occur.

By not detecting only the intersection but also its content a higher rate of TPR, True positive (detection) rate can be achieved.

If the intersection specifically needs to be detected, perhaps to improve TPR/FPR rate on another OoI then it could be done with several sensor types.

Lidar and radar could detect the lanes and road in the change of no curb. Also, identifiers such as traffic lights and light poles (and omission of such) could signal an intersection.

Cameras and optical sensors can detect it visually directly but also by interpreting road markings and traffic signs preceding the intersection.

3.7.1.4 Pedestrian Crossing

The crossing can be handled in a similar fashion as the intersection above. There, however, the importance of correctly interpreting the crossing increases with the decrease in distance to the pedestrian crossing.

A forward facing, Wide angle sensor is thus necessary, up to 180° is needed. Few static radars, if any is capable of this. Solid state lidar is ruled out by the same reason. A suite of several sensors can, however, be utilised.

Wide angle short range cameras coupled with a longer ranged sensor should satisfied set requirements. Reuse of already deployed sensors should be considered.

Concept solution 1: Two wide-angle cameras placed in front pillars directed slightly sideways us used in conjunction with a forward facing long-range camera.

Concept solution 2: A single rotating lidar in front of the vehicle could get 180° coverage. Vertical FoV should be considered and the placement puts the sensor in an exposed position.

Concept solution 3: Reuse sensors already in place, complemented with side-mounted sensors, both lidar and optical sensors possible. The height of the placement should be considered since low level might be unable to interpret scene if blocked or moving objects is obscured behind a close static object. High placement of sensors might be detrimental due to angles of close-in objects. Risk of blind spots if sensors not properly angled.

3.7.1.5 Persons

Detection of persons beside and on the roadway is paramount to enable safe approach. Farther distance means longer time to react. We are only regarding persons in front of persons walking beside the bus pose no danger to the vehicle or vice versa when there is no risk of collision.

A forward facing optical camera narrow FoV to ensure long detection range is a possible option. However, since range-estimation with optical cameras depend on interpreting the images with a known object and distance there should be additional sensors. Two combined optical sensors or stereo cameras could work but both radar and lidar enable measurements of distance with higher reliability.

Concept solution 1: One long range narrow FoV optical sensor combined with an additional sensor for ranging objects. Radars are a mature sensor-type and capable of ranging.

Concept solution 2: Two optical cameras paired as a stereo set. A wider separation will yield best ranging capabilities.

Concept solution 3: A Single long range narrow FoV camera for the farthest detection distances and a close range, wide-angle camera for shorter distances. Range detection still needed with an additional sensor.

3.7.1.6 Bicycles

Should reuse the same suite as the one for persons 3.7.1.5 above. The detection range is similar but speed could be needed to enable ACC functionality.

Concept solution 1: Reuse any sensor concept in 3.7.1.5 but ensure use of lidar, radar or stereo cameras with capability of measuring the speed of an object. The above third solution is not viable without additional sensors.

3.7.1.7 Vehicles

Vehicles such as other cars, buses and trucks are larger than a pedestrian or bicyclist. Radar is more viable than in the previous cases. Due to the presence of an intersection the detection range needed is wider closer to the autonomous vehicle. It does not need to be two sensors of the same type to function. Current long-range radar solutions are cheap, reliable and well tested and would be an excellent choice for long-range detection. If possible reuse of previously implemented sensors and sensors from other OoI and hazard detection should still be observed. The detection width needs to be in excess of two traffic lanes, preferable even four to ensure detection of vehicles incoming from intersecting road at the intersection.

Concept solution 1: LRR for long-range detection placed forward facing, estimated range-requirement for LRR should be no shorter than 125 m and preferably closer to 150 m with very high TPR. Complemented with wider SRR for short range detection. Placement of SRR could be with two sensors, one in each corner angled outward but with overlapping arcs in-front of the vehicle. Dead-zone should be negligible and range needed should not be above approx 30 m. The greater range could increase reusability in the detection of other OoI and hazard at other phases.

Concept solution 2: As Concept solution 1 but with long-range solid state lidar instead of the LRR.

Concept solution 3: Two rotating mechanical lidars slightly extended from each front corner of the autonomous vehicle. Gives close to 270° view if properly placed.

Advantages are high reuse-ability when detecting other OoI and hazards in later phases.

The sensors are expensive and exposed, vulnerable to collision, side-scraping and fender-benders if placed far down on the vehicle. The low vertical FoV must be taken into consideration. Placing the rotating lidars too high and the dead-zone in-front of the vehicle increases but the likelihood of damages to sensors could decrease.

Concept solution 4: An optical solution is possible, optical recognition of vehicles are reliable and cameras fairly cheap to implement. Long range detection is however much harder than close range detection optically. A sensor type such as lidar or radar for long-range detection and a solution consisting of at least one optical sensor to detect close range is viable.

3.7.1.8 Vehicle turn-signals

Current vehicle turn-signals are limited to visually indicate with light, only optical sensors such as cameras can hence detect the status of a turn signal. A forward facing camera is capable of detecting the traffic light and determining what status it has. Detection of turn-signals on vehicles in parallel lanes is not relevant for approach procedure, however, it is relevant to detect vehicles and their turn-signals in the intersection.

Distance and angle should include at least both lanes and vehicles in crossing roads at the intersection. Angle would, therefore, be close to 180° to detect OoI at the intersection.

3.7.1.9 Road Markings

Road markings already have solutions built on cameras. A lidar might be capable of detecting the contrast between road marking and pavement.

The area of interest is limited to the front of the autonomous vehicle and the boundaries of the road the vehicle travels on. There might be a use of detecting road markings for other roads intersecting to judge the intent of vehicles on crossing roads.

Potential hazards are if road markings are not properly detected due to being obscured or worn to nonrecognition.

3.7.1.10 Lane-ID

Related to road markings are the identification of lanes. This should be an additional step done in software but is dependent on collected sensor-data. By interpolating available data, such as occupancy by other vehicles on the roadway together with signs and road markings, lanes can be identified.

As such a single specific concept is not viable but a system must be capable of distinguishing lanes or at least with great certainty ensure the autonomous vehicle is driven where permitted and safe.

3.7.2 Docking Hazards

This section will outline solutions to the OoIs described in section 3.6.5.2, a summary of these is available in table 3.4.

Distances to persons and the total amount make potential danger to persons high. There is also a high level of risk with obscured OoI leading to potential hazards.

Placement of sensors need to be properly considered and the short distance to OoI makes no or very low total area of dead zones paramount.

3.7.2.1 Platform

The platform at the bus stop is one of the most significant and distinguishing features of the bus stop. By detecting the platform the autonomous vehicle can determine where to position itself, where free space is needed and where persons can be positioned without risk of being harmed.

The platform can itself be detected by interpreting sensor data. It can also be mapped by a GPS with high accuracy.

If this data is not available or possible to ensure with high confidence then the existence and position of the platform can be interpolated from other objects.

To ensure high reliability and safety a most likely scenario is to use both tools where the sensors are reused from solutions of other related OoI detection. Detection of persons on the platform and the curb are some related OoI.

Concept solution 1: GPS-map the position of the bus stop.

Concept solution 2: Use specific sensors to detect the platform. Lidar and optical most reliable to detect the platform from the vehicles point of view.

Concept solution 3: Interpolate existence of the platform from related data retrieved from sensors used for OoI probably to be positioned on the platform.

Concept solution 4: A combination of the previous concepts.

3.7.2.2 Curb

Detection of the curb is needed to ensure a smooth ride for passengers and a safe docking. If the autonomous vehicle docks a long distance from the curb departing passengers might misstep and injure themselves. Embarking and debarking for disabled passengers, and passengers with strollers, baby carriages and other wheeled contraptions have a less comfortable process of embarking and disembarking if the vehicle is too far from the platform.

Placement of the docking vehicle is therefore important and should strive to be as close to the curb as possible.

Failure to detect the curb might lead to side-scraping the vehicle or even the vehicle venturing up on the platform.

There can be no persons between the platform and curb and the vehicle, this should be considered a hazardous situation.

Concept solution 1: Lidar aimed at the curb, preferably placed close to the ground but at an angle. Mapping the positioning of the curb and storing position and approach speed. This can be used to build an internal map.

Concept solution 2: Optical sensors to map angles for approach, distances can be measured if own vehicle is in the picture and used as a reference. Stereo cameras can be used for some distance measurement.

Concept solution 3: Radar solution, specific distance not ensured with high probability but detection of the curb is possible.

3.7.2.3 Persons

Due to the higher occurrence of persons at the bus stop than during the approach the detection system needs to be able to handle multiple OoI at the same time. Ultrasonic can currently not be implemented with high enough reliability and has been discarded. The persons on the platform are to be properly identified and it must be possible to map these in relation to the autonomous vehicle. If a person is between the platform and the vehicle then this must be detectable.

The expected area to detect persons in is in front of the vehicle and to the side facing the platform, this means approximately 270°. (135° cone in front and 135° to the side of the vehicle).

Concept solution 1: All camera solution, possible with referencing or stereo to enable measurement of distance or ensuring no persons is in the path of the docking autonomous vehicle. Placement should be fairly high up on the vehicle angled downwards to lessen dead-zone close to the vehicle.

Concept solution 2: Lidar-based solution, two rotating lidars on the two corners facing the platform will satisfy detection of persons on the platform and on all positions the vehicle can traverse.

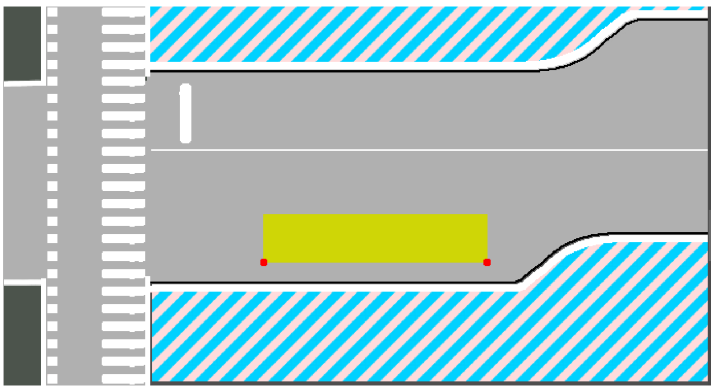

Figure 3.13: Red dots: Placement of Lidars on the bus for detection of persons in concept solution during docking.

The horizontal angle must be regarded and potential dead zones. Due to the workings of lidar, if the placement is low, there is a risk of obstacles being obscured or in the shadow of closer objects. To ensure not missing moving OoI in potential risk of intersecting the vehicle's path the position of the lidars could be above head-height.

The Lidars need to extend beyond the sides of the vehicle slightly which means higher exposure to the elements and impacts.

Solid state lidars could, if sufficiently cheap be deployed and used. This needs several sensors to get good coverage or rely on new and upcoming sensors. Current FoV of 120° is somewhat low.

3.7.2.4 Bicycles

Most of the reasoning in the section about detecting persons 3.7.2.3 is applicable in the detection of bicycles. However, there is a small but tangible risk of a bicyclist approaching from the rear of the autonomous vehicle and positioning him/herself between the bus and platform. Likewise, there could be a collision if the bus suddenly turns into the docking position and the bicyclist is approaching fast and is oblivious to the actions of the autonomous vehicle.

Therefore in addition to detecting oncoming bicyclists approaching from the front, detection aimed at detecting bicyclist approaching from the rear should be added.

Concept solution 1: A MRR is capable of detecting both the presence of a bicyclist and speed of approach.

Concept solution 2: A camera solution is possible, either with referencing of known distances or with a stereo solution.

3.7.2.5 Front Overhang

Detecting whether or not there are any obstacles within the space, on the platform, the front overhang will occupy is important, both for the safety of whoever occupies the space on the platform but also in order to guarantee the bus doesn't damage itself. However, the overhang enters the platform with fairly low speed so while detection of pedestrians is necessary, the overhang being the reason for a fatality is very small and the need for detecting what kind of obstacle is close to the overhang is unnecessary. The space on the platform which the overhang will occupy during departure will be referred to as the overhang zone.

Concept solution 1: Use an ultrasonic sensor to detect the presence of an obstacle. Specifying what kind of obstacle is not really necessary. This is most likely the cheapest solution if no other specific sensor is available for reuse.

Concept solution 2: Usage of optical cameras to detect obstacles. Works well for complete solutions where there already are cameras facing the side of the vehicle with an arc extending and encompassing the specific overhang area.

3.7.3 Departure Hazards

During the departure phase, many of the solutions to the presented hazards are identical or nearly identical to earlier phases.

3.7.3.1 Traffic Lights

Identical with 3.7.1.1

3.7.3.2 Traffic Signs

Identical with 3.7.1.2

3.7.3.3 Intersection

The solution is identical to 3.7.1.3

3.7.3.4 Pedestrian crossing

Identical to 3.7.1.4

3.7.3.5 Rear Overhang

Very similar to 3.7.2.5 but instead of front overhang during the departure It's the rear overhang that is relevant.

Concept solution 1: Ultrasound Works well in low-speed situations. Even though the information given by the sensor is limited to the number of obstacles within the sensors FoV and the distance to them, this is sufficient enough to determine whether or not the overhang will hit anything.

Concept solution 2: Camera A camera could detect whether or not anything has entered the overhang zone or not.

Concept solution 3: Lidar Would work similarly to a camera but with the added benefit of range detection as well.

3.7.3.6 Platform

Identical with solution mentioned in 3.7.2.1

3.7.3.7 Curb

Identical with solution mentioned in 3.7.2.2

3.7.3.8 Pedestrians

Identical to solution mentioned in 3.7.1.5

3.7.3.9 Bicycles

Identical to previously mentioned solution, see 3.7.1.6

3.7.3.10 Vehicles

The automotive vehicle needs to exit its parking spot and move left into a new line, making sure no vehicle approaching at speed from the rear is critical to prevent a collision. A solution is similar to the one presented in 3.7.1.7 but applied on the rear of the vehicle.

Concept solution 1: Rear mounted radar has the capability to see far enough and measure the speed of any vehicle.

Concept solution 2: Camera or Stereo cameras could solve this as well.

Concept solution 3: Lidars are potentially applicable as well.

3.7.3.11 Vehicle turn-signals

Identical to solution mentioned in 3.7.1.8

3.7.3.12 Road Markings

Identical to solution presented in 3.7.1.9

3.7.3.13 Lane-ID

Identical to solution presented in 3.7.1.10

3.8 Complete vehicle concepts

This section will outline some result of our brainstorming session when combining and arranging the solutions given in previous sections 3.7.1 - 3.7.3.

3.8.1 Lidar based Simultanious localisation and mapping (SLAM)

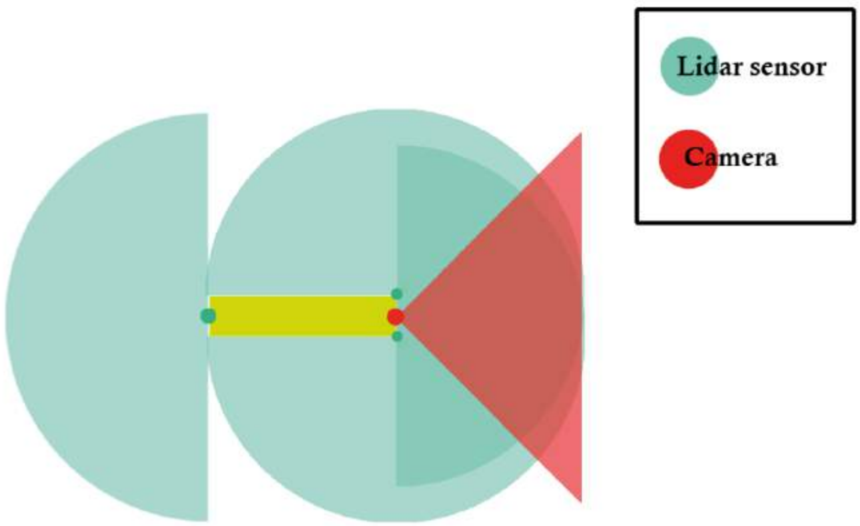

Figure 3.14: Concept 1: Lidar-based SLAM with an optical sensor.

Concept generated in a brainstorm session where the idea was to create a concept with a minimal amount of sensors. Taking inspiration from various current projects such as Einrides autonomous truck T-Pod. This concept uses three lidar sensors, placed one in each front corner and one in the rear. A camera in front handles visual cues such as traffic lights and contents of traffic signs. Continuing on the previous design to achieve better coverage a variant was envisioned. Additional radar was mounted in front and rear. An additional lidar is added to total four, one in each corner. This added lidar gives at least two sensors capable of detecting an item in any given direction. The added sensors increase the redundancy significantly.

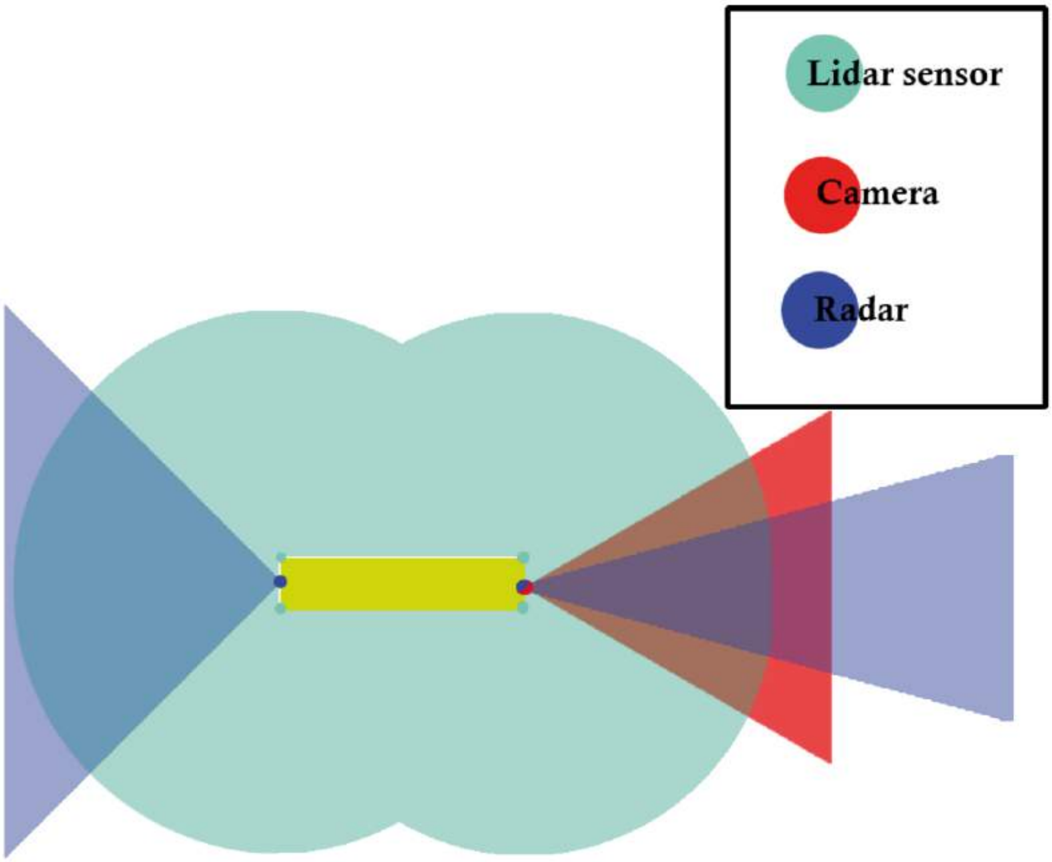

Figure 3.15: Concept 2: Lidar-based SLAM with extended sensor suite.

3.8.1.1 Characteristics and variants

The current lidar sensors give a probable range of detecting vehicles up to a distance of approximately 120 m, however, some are capable of detecting large targets up to almost 200 m during good conditions. The conservative number of 120 m is sufficient to meet requirements in use-case but with small margins. The lidars might not be able to detect a traffic light, a traffic sign or any targets consisting of darker materials at sufficient range.

Pros

- Low number of sensors
- Good redundancy capabilities
- Low Data with sensor-fusion

Cons

- Lidar solution may not be optimal for long range detection.
- Low sensor overlap resulting in low redudancy.

Pot. Hazards

- Obscurification due to sensor placement
- No turn-signal detection in rear
- Low redundancy, single point of failure

3.8.2 Camera based solution

Automotive cameras are cheap, a common sensor and variants usually consist of the same sensor and different optics. They are easy to implement physically but rely on software recognition. The sensor suite consists of nine to ten cameras. A variant

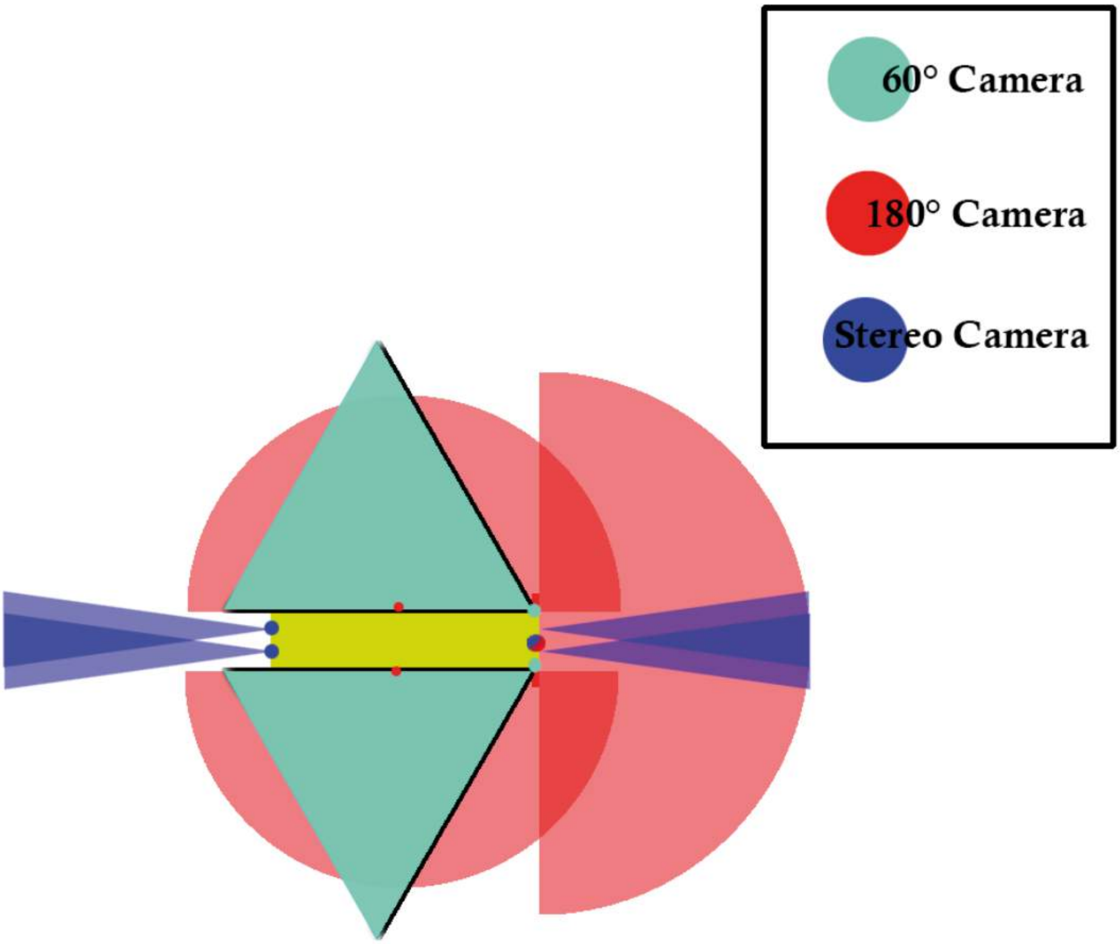

Figure 3.16: Concept 3: Sensor suite consisting of only cameras.

with two separate front proximity sensors instead of the single 180° forward-facing camera is an option. Choosing two cameras in front gives better optical properties of the cameras due to less vignetting and/or optical distortion of the lenses.

Pros
- Most likely only one supplier
- Good redundancy capabilities
- A lower number of sensors
- Low data with sensor-fusion

Cons
- Poor long range detection

- Reliant on only one sensor type and sensor data

3.8.3 Full coverage, all sensor-types

A concept not limited to any specific sensor-types but a combination of each system, leveraging each sensor-types advantages.

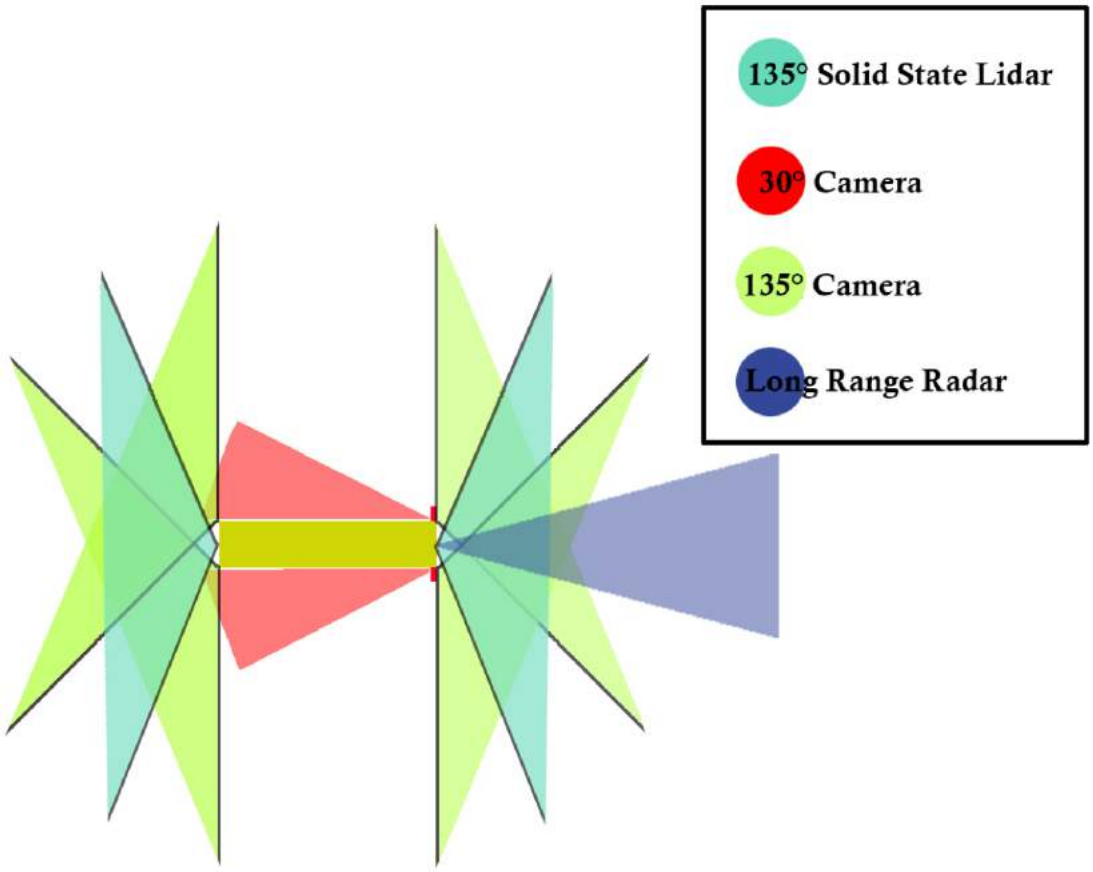

Figure 3.17: Concept 4: Sensor placement overview

The vehicle is equipped with forward and rear-facing solid state lidars, with these the environment can be mapped and as an active sensor oblivious to night/day cycle and mapping continues while the vehicle is stationary. Solid state lidars used in this regard is primarily for mapping and should be fairly wide-angled horizontally but not necessarily vertically. A high vertical angle can be utilised if the function of the SSLs is extended to localisation as well as mapping. There is a forward facing optical camera determines traffic signs and traffic lights. Long range radar detects vehicles in front. Since the relative speed is lower to moving targets in the rear of the vehicle the use of a medium range lidar gives a wider detection arc. This can, however, be exchanged to an identical sensor as the forward facing lidar if the detection arc meets requirements of the use-case.

In each corner, there are cameras used for side-wise detection of bicycles and pedestrians. These should be fairly wide to cover areas. If needed a central camera both rear but most importantly in front could be added to ensure no dangerous blind spots.

The frontal blind spot can also be handled by adding an ultrasonic sensor. Two cameras positioned where the side-view mirrors are positioned look down the sides of the vehicle. They are to detect persons on the outside of the vehicle when turning out into traffic or potential overhang and necessary free space.

Most likely needs mapping tools to properly navigate.

Pros
- Robustness of applying several sensor technologies
- Sensor overlap
- Multiple redundancies in front of the vehicle

Cons
- High dependency on proper sensor fusion
- Lots of sensors of different types
- A high number of sensors
- Potential high computational power needed
- Lots of wiring needed
- Power-draw might be an issue

Pot. Hazards
- Solid state lidars are not well tried and tested yet, potentially poor mapping of an environment.
- Blindspot/poor vision in front corners when turning.

3.9 Workshop evaluation

The concepts generated in previous section 3.8 was presented at a workshop at Volvo Bussar AB. The concepts were evaluated by several metrics, but none of the concepts presented was found satisfactory or viable in a realistic scenario.

Further on the authors had overestimated the capabilities of lidar and somewhat underestimated the capabilities of both radar and ultrasonic. Both radar and ultrasonic are well-tested and proven technologies and have been used in the automotive industry for a long time with good results and reliability. Lidar should, therefore, be used for SLAM and not detection of objects. The other sensors should be utilised in conjunction to provide high reliability and redundancy.

It is very important to cover all approaches and ensure redundancy. A sensor is no good if it fails and, if there is a single point of failure in the system, the vehicle is inoperative. As in the aerospace industry, there are several independent systems for important functions.

If a vehicle is equipped with a single sensor and it fails, the system either detects the sensor being faulty or worse getting false information. If there are two sensors and one fails, the system might know there is a fault, but not which sensor to rely on. When three sensors are present and one fails, this is detectable by the system and it can continue to function. Therefore a triple redundant system greatly increases the potential for the vehicle to continue to function without interruptions.

4

Results

The results of our investigations and generated concepts will be combined and presented here.

4.1 Final Concept

The final concept does not encompass any of the processing units, algorithms or specific sensors but it will contain sensor types and arcs where these should be aimed. Specific angles are not present but estimated in pictures. The specific angles must be tested and verified before actual implementation in a vehicle. The final concept assumes some data is available through interconnection with infrastructure and the fleet of autonomous vehicles. Such as information from traffic lights.

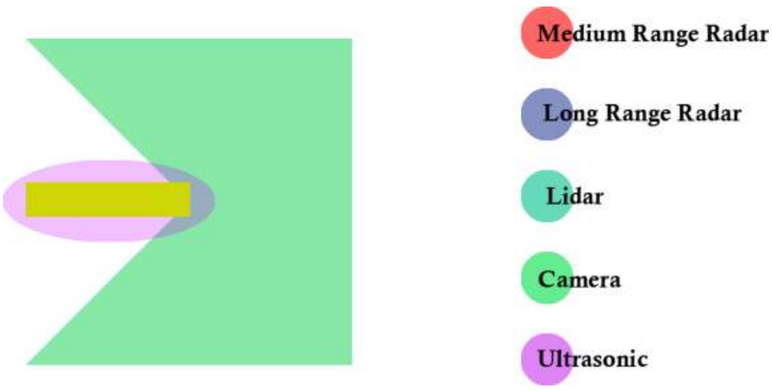

Figure 4.1: Detection arcs of cameras ultrasonic sensors of final concept.

To ensure detection of any close-up objects the vehicle will be equipped with proximity ultrasonic sensors. In-case the sensor-suite reboots and there is no memory of object classification the ultrasonic sensors can act as a backup and detect obstacles. The ultrasonic sensors are situated all around the vehicles lower edge.

The front-aiming camera is responsible to detect any new and unmapped signs, traffic lights and together with sensor-fusion and the other sensors classify objects. The camera will also be a fall-over when information about the status of the traffic lights is unavailable. If the vehicle is redirected through a different route the camera will enable functionality at traffic lights and follow traffic signs when communication from the infrastructure is not available. Cameras overlapping radar is to ensure no single point of failure, they will work in conjunction with the radars to detect and classify objects.

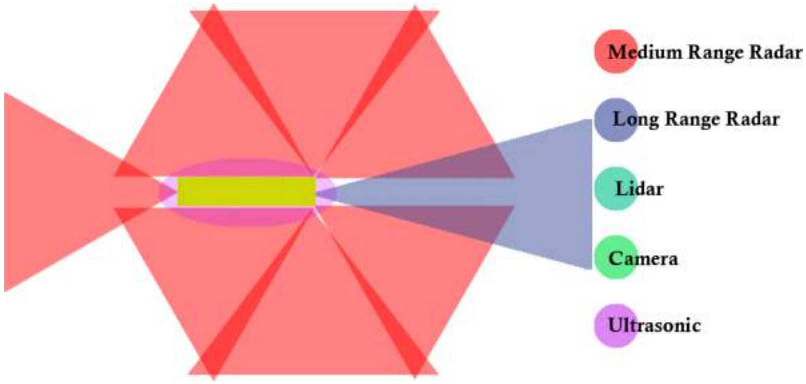

Figure 4.2: Radar coverage of final concept.

Radars are a mature, tried and tested sensor-type capable of detection on an object-level. This makes radars the currently most well-suited sensor for long to medium range detection. They are responsible for detecting vehicles, movable objects in the lidar-mapped environment. Radars are also capable of determining the relative velocity of other objects.

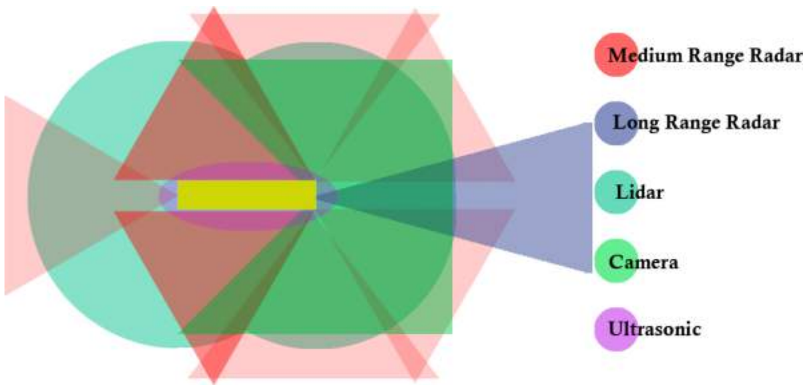

Figure 4.3: Total sensor coverage of final concept.

The lidars are situated in all four corners of the bus. The lidars are mainly responsible for SLAM and having one in each corner enables the lidars to remove the blind spots that are under each lidar. The rear lidars are mapping in case the vehicle needs to reverse. The gathered data is shared between vehicles if a fleet of similar buses is deployed.

We propose four rotating lidars as per section 3.8.1 and as can be seen in figure 3.13. When new future solid-state lidars arrive on market they are potential candidates for the same function.

4.1.1 Additions to concept

The concept would utilise an internal map containing good data for where to expect the bus stop. If a fleet of similar is in use they should pool their mapping data to ensure smooth handling of prolonged obstacles such as broken down vehicles on the road or road work limiting traffic flow.

Sensors could be incorporated on each bus stop to increase accuracy, calibrate the vehicle's sensors if needed and increase reuse of resources. If there are specific needed data specifically on a bus stop then instead of building ten buses with ten sensors this could be one sensor on the specific bus stop, thus decreasing cost.

Cameras in all positions a human driver would want to look from, enable remote controlling in those cases the autonomous system is unable to progress due to sensor faults or accidents.

5

Conclusion

This chapter will contain our final thoughts and summarised recommendations of future development from the gained ideas of the chapters Results 4 and Discussion 6.

5.1 Results of thesis

The initial goal of the thesis was given new input to an on-going development project. However, designing a complete sensor-suite is really hard. Not only is the selection of sensors already obsolete when the thesis is done but also the specific sensor-models cannot be determined without actual tests. It is not really feasible of selecting specific sensors on a purely theoretical basis.

5.2 Recommended process

The methodology of breaking the procedure of an autonomous vehicle down to small components and investigating these separately worked really well in identifying needed capabilities. This compartmentalisation enables parallel development of multiple projects simultaneous.

The needed capabilities should be combined between all the separate use-cases to build a complete solution.

5.3 Implementation

Since producing a completely autonomous vehicle in the first production run is impossible the following changes to the final concept is proposed:

- The vehicle should be controlled by an onboard driver but future iterations should be controllable remotely by an off-site controller if needed. This means cameras should be installed in the rear and in side-view mirrors to give ample view of surroundings.

- Multiple independent sensor-suites should be mounted on the same vehicle. Testing, training and evaluation will then be available from the same data.
- No single point of failure should be present in sensor coverage, connectivity or computational power as outlined in section Workshop 3.9.

There are no guarantees that current sensor capabilities are sufficient to ensure compliance with future requirements of autonomous vehicles.

The future demands and requirements of the autonomous vehicles may also in-turn change or in other ways limit the viability of current sensor requirements.

6
Discussion

In this chapter will we discuss our results and how the approach could improve future results if a similar topic is undertaken.

6.1 Current sensor limitations and possible contributing development

There are a lot of sensors in development and accompanying units designed for computation, hardware accelerated recognition and more.

While limited to only existing sensors makes the collection of data more reliable, it does limit the potential use of sensor types. Solid state lidars are one not yet widely deployed but are a promising technology.

During the thesis's work, it has been apparent that the development is progressing at a very high speed. Several new sensors and models have been not only unveiled but also made available for ordering during the duration of this thesis.

In essence, the next generation vehicles might not use the current sensors but some far more sophisticated sensors.

6.2 Limitations of generated concept or use-case

The generated concept is not as of yet capable of determining between force-able or non-force-able objects. This needs hands-on test and verification with sensors we have not had access to. There also need extensive training of neural networks or algorithms for identifications. This was excluded from the use-case and hence not available.

Furthermore, even if proper identifications of objects is accessible, how can the vehicle determine if for example a cardboard box is empty and not filled with animals or objects which can damage the vehicle? This is very hard to design and implement.

Since this thesis does not look into related systems such as recognition and data processing, there might be a potential candidate to these above problems that have been omitted. The desired solution might not be solved by more raw sensor-data but rather the software processing of the available sensor-data.

6.3 Potential continued improvements of concept

This thesis did not investigate the use of infrared optical cameras. These cameras are capable of detecting heat-sources such as persons and animals. This data could be fused with other data to better interpret object level-data. Such if the radar return is of a person, structure or even wildlife.

Further, the incorporation of sensor-data from other sources than the vehicle itself could be an interesting topic to investigate.

6.4 Incorporation of supporting infrastructure

During the workshop, there was a question regarding why there were no communications between vehicle and infrastructure. One example of such communications would be traffic lights capable of communicating with the vehicle and informing if the autonomous vehicle is allowed to proceed or not. During the investigations we deemed the modification of infrastructure to be a big of a step to accommodate autonomous vehicles. There are also potential risks of faulty communications. However, at the deployment of a fleet of autonomous vehicles and at a specifically designed depot, bus stop or infrastructure constructed for this fleet, it could be very viable to design the infrastructure for accommodating the vehicles as well as possible.

By installing supporting infrastructure all autonomous vehicles could potentially be remotely operated instead of having onboard systems providing sensor-data. A city could, for example, have complete camera coverage and use these to control autonomous vehicles.

A further development area to investigate would be cloud-computing of raw data if the vehicle fleet is interconnected. Perhaps very relevant since discussions of using vehicles as hosts for 5G-transmissions in the next generation of mobile communications. If all vehicles could pool raw data in real-time an object can be observed from several angles and collectively classified by several vehicles.

6.5 Improvement of methodology

This section outlines what we think could have been done to improve the methodology to give a better or more reliable result.

During the workshop, the authors of this thesis realised several things, not only the part about infrastructure above.

There should have been more and earlier workshops to ensure we would not miss anything important. Reality checks of current progress and even getting a different point of view could potentially have optimised the work with the investigations.

The classifications of objects should not necessarily be divided between persons and vehicles but rather between stationary structures and mobile objects. The mobile objects should then be subdivided between force-able objects such as boxes, bags, branches etc. and non-force-able objects such as persons, vehicles, traffic-cones and more.

6.6 Sustainability

The vehicle envisioned in this thesis would be a fully autonomous vehicle. This means no need for the vehicle to change drivers and potentially the vehicle could be running most of the day without diverting to the depot for driver-change. If this is possible to achieve a single autonomous vehicle could potentially replace more than one regular vehicle.

While the autonomous vehicle would most likely be more expensive to construct in regards to resource expenditure, this could be offset with the possibility of carrying more passengers when no driver or driver seat is needed inside of the vehicle. The softer regulation of acceleration and deceleration could also convince more motorists of taking the bus further lessening emissions.

As it would be a fully electric vehicle it could potentially be beneficial to emissions and the air quality in cities. Note however that the energy must come from somewhere and the transition to all-electric vehicles does not mean less emissions but rather higher need for electricity.

The sensors used all need some type of computational power, and the sensors for both lidars and cameras are built on CMOS-technology. The scrap from scrapped semi-conductors is hard to recycle. When a single vehicle replaces several regular vehicles this could ultimately result in a net positive or at least a zero-sum situation.

The probably largest impact on the environment would be the need for batteries. Current battery technologies utilise lithium which has a mining procedure which produces a lot of slag and debris.

6.7 Ethics and lawmaking

One of the biggest hurdles of enabling fully autonomous vehicles on the roads must be the ethics and laws. Who is guilty and responsible if a fatal accident occurs? The manufacturer of the vehicle, the operator or the other party? How can this be decided or formulated in law?

This is apparently not going to be a fast process for good reasons. A slow and systematic approach to the issue is necessary. The engineer or system designer must always put safety first and foremost. The single best practice is to have a zero accident vision, safety in autonomous vehicles must always be the most important factor.

Bibliography

[1] Continental AG (n.d.) Advanced-Radar-Sensor-ARS441 (no date). Retrieved May 28, 2018, Available at: https://www.continental-automotive.com/en-gl/Passenger-Cars/Chassis-Safety/Advanced-Driver-Assistance-Systems/Radars/Long-Range-Radar/Advanced-Radar-Sensor-ARS441

[2] Schmid, K., Carter, J., Waters, K., Betzhold, L., Hadley, B., Mataosky, R., & Halleran, J. (2012). Lidar 101: An Introduction to Lidar Technology, Data, and Applications Coastal Remote Sensing Program. Revised. Charleston. Retrieved from https://coast.noaa.gov/data/digitalcoast/pdf/lidar-101.pdf

[3] Hata, A. Y., & Wolf, D. F. (2016). Feature Detection for Vehicle Localization in Urban Environments Using a Multilayer LIDAR. IEEE Transactions on Intelligent Transportation Systems, 17(2), 420–429. https://doi.org/10.1109/TITS.2015.2477817

[4] Leddar Solid-State LiDAR Technology Fundamentals. (n.d.). Retrieved February 22, 2018, from https://leddartech.com/technology-fundamentals/

[5] Velodyne. (2017). Real-Time 3D LiDAR Wide Field of View and High Frame Rate. Retrieved from http://velodynelidar.com/docs/datasheet/63-9194_Rev-F_HDL-64E_S3_Data Sheet_Web.pdf

[6] Velodyne. (2007). Velodyne's HDL-64E: A High Definition Lidar Sensor for 3-D Applications. 2007. White Paper, 7. Retrieved from http://velodynelidar.com/lidar/products/white_paper/HDL white paper_OCT2007_web.pdf

[7] Velodyne LiDAR. (n.d.). HDL-64E Manual S3. Retrieved from http://velodynelidar.com/docs/manuals/63-HDL64ES3 REV J MANUAL,USERS AND PROGRAM GUIDE,HDL-64E S3.pdf

[8] LeddarTech. (2017). LEDDARVU 8-SEGMENT SOLID-STATE LIDAR SENSOR MODULES MULTI-OBJECT, WIDE-BEAM OPTICAL DETECTION AND RANGING OVER EIGHT SEGMENTS THE SMALL, AFFORDABLE, VERSATILE LIDAR. Retrieved from https://d1wx5us9wukuh0.cloudfront.net/app/uploads/dlm_uploads/2017/05/Spec-Sheets-LeddarVu-4decembre2017-web.pdf

[9] Stanford Seminar-Solid State LiDar for Autonomous Vehicles,Security, Industrial Automation, 3D Maps - YouTube. (n.d.). Retrieved February 22, 2018, from https://www.youtube.com/watch?v=uPqzo29Q9Wc

[10] Bosch Gmbh, R. (no date) 'Ultrasonic-based driver assistance systems'. Available at: https://www.bosch-mobility-solutions.com/media/global/products-and-services/passenger-cars-and-light-commercial-vehicles/driver-assistance-systems/construction-zone-assist/product-data-sheet-ultrasonic-sensors-generation-6.pdf (Accessed: 28 May 2018).

[11] Liu, W., Li, S., Lv, J., Yu, B., Zhou, T., Yuan, H., & Zhao, H. (2017). Real-Time Traffic Light Recognition Based on Smartphone Platforms. IEEE Transactions on Circuits and Systems for Video Technology, 27(5), 1118–1131. https://doi.org/10.1109/TCSVT.2016.2515338

[12] TIDUB74 – December 2015 Automotive 1.3M Camera Module Design with OV10640, DS90UB913A and power over Coax Automotive 1.3M Camera Module Design with OV10640, DS90UB913A and power over Coax. (n.d.). Retrieved from http://www.ti.com/lit/ug/tidub74/tidub74.pdf