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"Konzept zur Nachbildung von Umweltsensoren für Assistenzsysteme"

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1 Introduction

1.1 Overview

This thesis deals with Advanced Driver Assistance Systems (ADAS) and their environment sensors in the light of requirements for sensor stimulation systems. For these topics the books “Handbuch Fahrerassistenzsysteme” [1] by Winner et al. and the “Fahrstabilisierungssysteme und Fahrerassistenzsysteme” [10] by Reif have been the main sources for information about the state of the art. For one such environment sensing principle, ultrasonic sensors, a proof of concept sensor stimulation is presented. In chapter 1 the current state of the art and the motivation for this thesis are presented. Chapter 2 portrays the core aspects of relevant ADAS and in chapter 3 an overview about the environment sensing systems for ADAS is given. Chapter 4 discusses the core aspects for the design of sensor stimulation based test systems. Chapter 5 deals with the realization of a proof of concept for an ultrasonic stimulation system. Finally, the concluding chapter 6 gives a discussion and outlook on what will be done next.

1.2 Problem Statement

The costs of sensors for ADAS have been continuously declining, while their capabilities have been improving. This is a driving factor behind the continuous movement of ADAS into the mass market [4]. In terms of Passive Safety in automobiles the development process has come very close to its full potential, further gains can therefore only be achieved with huge effort. Active Safety is the next step to reduce the risks drivers are exposed to in traffic [1]. A data analysis, conducted by Treat and his coworkers, of 2258 accident reports investigated the causes of accidents. They found that human failure as accident cause was present in 93%, environmental factors as cause were present in 34% and vehicle factors were present in 14% of all accidents [5]. Despite the problems with defining the term “cause” these results suggest that ADAS can potentially improve the consequences of the majority of accidents. The introduction of the Breaking Assistance System (BAS) by Mercedes Benz reinforces this perspective as the amount of rear shunt accidents by newly registered cars dropped from 10.5 per 100000 newly registered cars in 1998 to 9.7 in 2000. The BAS recognizes when a driver breaks in an emergency situation. In this situation the brakes are used immediately at their maximum capacity, whereas the average driver brakes a little, realizes that his breaking is not sufficient and only then brakes at maximum capacity [6]. Assistance systems such as these have come a long way since then and can now warn the driver of an impending collision and will even initiate a partial brake to reduce damage and grab the drivers' attention. Volvo and Daimler amongst others have pledged to offer cars on the market by 2020 that will not cause accidents by themselves. A goal which is only achievable through ADAS [3][4].

Current ADAS sense their environment and process this information in order to inform the driver and/ or to make decisions and act upon those decisions, influencing the driving process as a result. Through this co-influence on the driving task all situations which driver and automobile experience become relevant test situations, making it hard to fully test ADAS. The effective development of ADAS requires testing on each stage of development to gain information about whether the ADAS are functioning as expected and how well the interaction between humans and ADAS works. These tests need to be as reproducible and reliable as possible. Right now there is no system which can accomplish this task completely, especially not in the final stage of the development process, when the ADAS have already been integrated in the car. Figure 1-1 shows how such a system would look like.

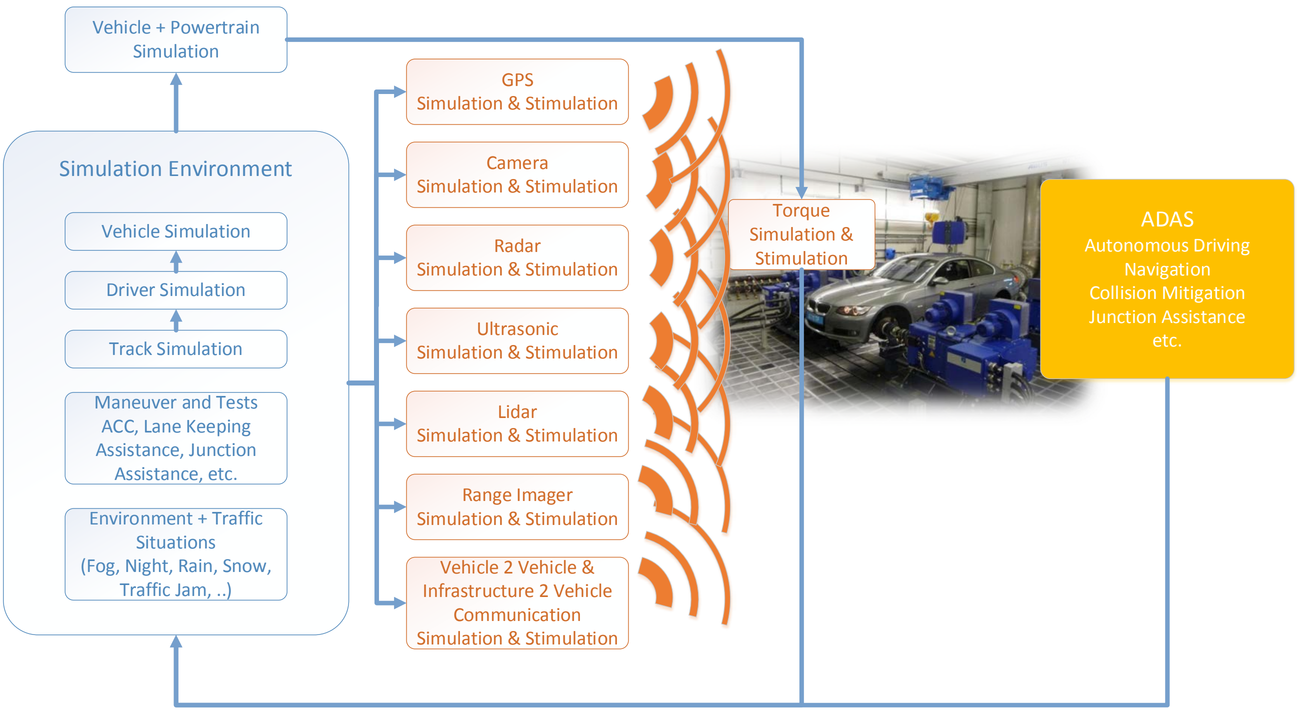


Figure 1-1 Overview of a Vehicle in the Loop ADAS Test System

1.3 Goals

This thesis aims at achieving two goals. Firstly, the frame in which Advanced Driver Assistance Systems and their sensors are used, will be established and the requirements a Software in the Loop (SiL) or Vehicle in the Loop (ViL) test system would have to fulfill in order to be an essential component throughout the ADAS development process will be deduced from that. Secondly a proof of concept system for ultrasonic stimulation will be created.

2 Portrayal of Relevant Assistance Systems

In order to decide which capabilities a test system for assistance systems needs, it is necessary to know the frame into which the characteristics of assistance systems fit. In order to gain this scope the assistance systems need to be described. Every assistance system has been implemented by different manufacturers in multiple ways. Tests will have to be tailored to each specific implementation. Discussing all currently existing versions would exceed the size of this document by far, but there are several angles from which one type of assistance system has common attributes with its siblings. Every assistance system has a purpose which is aimed at serving needs by improving or taking over, either in part or in full, aspects of the driving task. Also, they achieve different levels of automation which come with different demands on error-free function, error detection and behavior during failure. Additionally, each assistance system makes decisions based on information which have undergone processing at several layers before being used. The assistance systems will be viewed through these lenses to keep their characterization short.

2.1 The Driving Task

According to Rasmussen [7] human behavior is structured in three layers. The driving task is separated into these layers by Donges [8] as shown in Figure 2-1 by Winner [1]. The largest timescales correspond to navigation which is mainly about choosing a route and timing. On a given route trajectory planning is about which course the car should take and at which speed. This trajectory is then followed by activities associated with stability. As Figure 2-1 suggests human performance is strongly intertwined between knowledge-based, rule-based and skill-based behavior. Although the test system is not intended to test human interaction many performance criteria of ADAS will be rooted in how they influence human driving task performance.

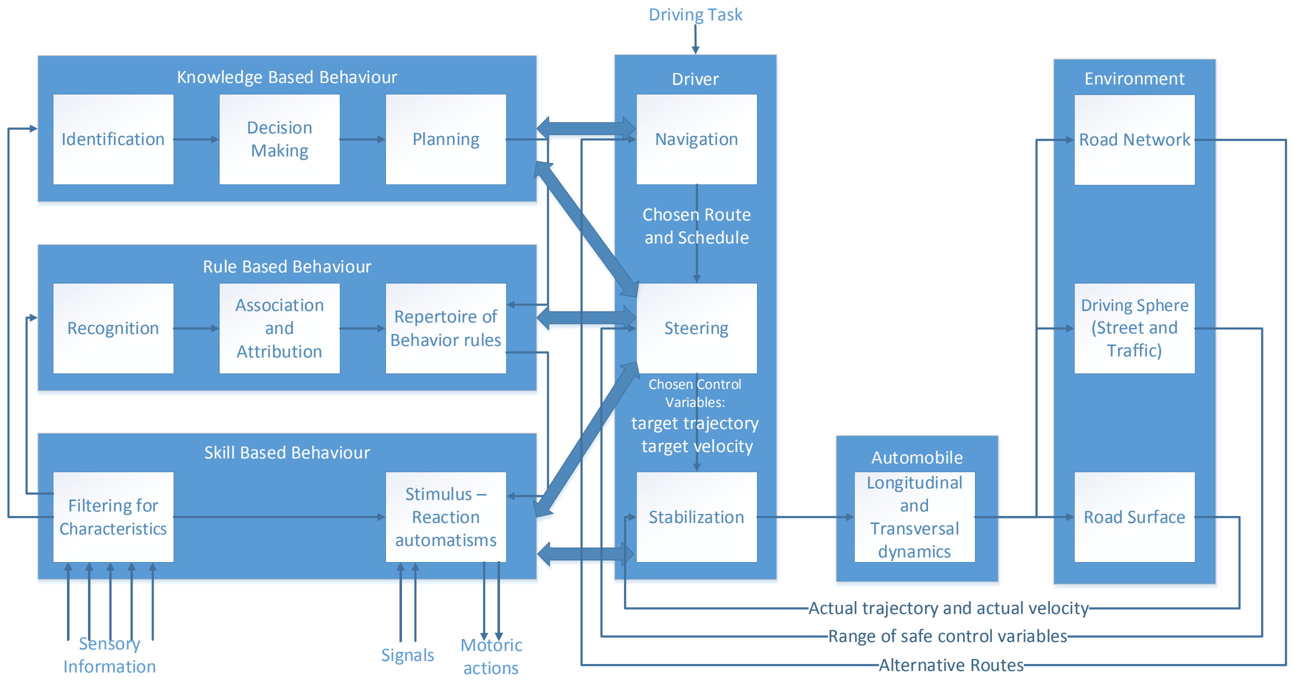


Figure 2-1 The Driving Task

Different levels of human capability steer how humans perform the three major levels of the driving task. Navigation is performed by knowledge based behavior, steering or trajectory planning occurs through rule based behavior and stabilization or control is performed through automatic motoric skills. Assistance systems can be organized by which part of the driving task they influence. Whereas assistance systems such as the anti-lock breaking system influence the stability layer, are already well established and have control capabilities beyond humans, most new assistance systems also influence trajectory planning and in some cases Navigation. In these domains optimum human comprehension of the current and anticipated future traffic situations are beyond machine performance. As human performance can vary there are already large amounts of situations where ADAS can step in and perform better than humans.

2.2 Purpose of Assistance Systems

Assistance system development processes are always initiated by certain demands. The purpose of an assistance system is to satisfy that demand through achieving a goal. This goal is then implemented through a certain functional task. Assistance systems can be described very briefly and clearly by analyzing their purpose in this manner [1].

Assistance Demand

In order to develop an assistance system there must be a demand. This demand is usually related to safety or to comfort. The developed assistance system is always aimed to satisfy one or both needs.

Assistance Goal

The goal states how the assistance system can improve the user's satisfaction of their needs. The formulation of the goal focuses on what change in the user's experience is supposed to happen.

Functional Task

The functional task describes which capabilities the assistance system needs in order to improve user satisfaction. The formulation of the functional task focuses on what the end result of the assistance function should be. The functional task does not describe the whole function of the assistance system. Usually, any realization of a functional task requires a large amount of additional details on lower level functionality.

2.3 Automation Level

The automation level describes to which extent the assistance system influences the driving task. Five different levels are discerned. Depending on which level of automation an assistance system reaches different legislation and safety requirements apply. The Automotive Safety Integrity Level (ASIL) of ISO 26262 is established by performing a risk analysis of a potential hazard by looking at the severity, exposure and controllability of the vehicle operating scenario. The safety goal for that hazard in turn carries the ASIL requirements [16]. With increasing automation the projected safety risks also increase, raising the required amount of verification and validation. The description and amount of levels can change between nations and geographic regions. The Society of Automotive Engineers International (SAE International) provides an overview of the most prominent categorizations [16] including the categorization given here by the German Federal Highway Research Institute (Deutsches Bundesanstalt für Straßenwesen (BASt)) (Appendix A)

L0 Driver only

The driver permanently performs all transversal and longitudinal control even when enhanced by warning or intervention systems.

L1 Driver Assistance

The driver permanently has control. Only one task can be automated to a certain extent.

L2 Partly automated

The system takes over one or more parts of the driving task. The driver has to permanently monitor the system and be prepared to take over control at any time.

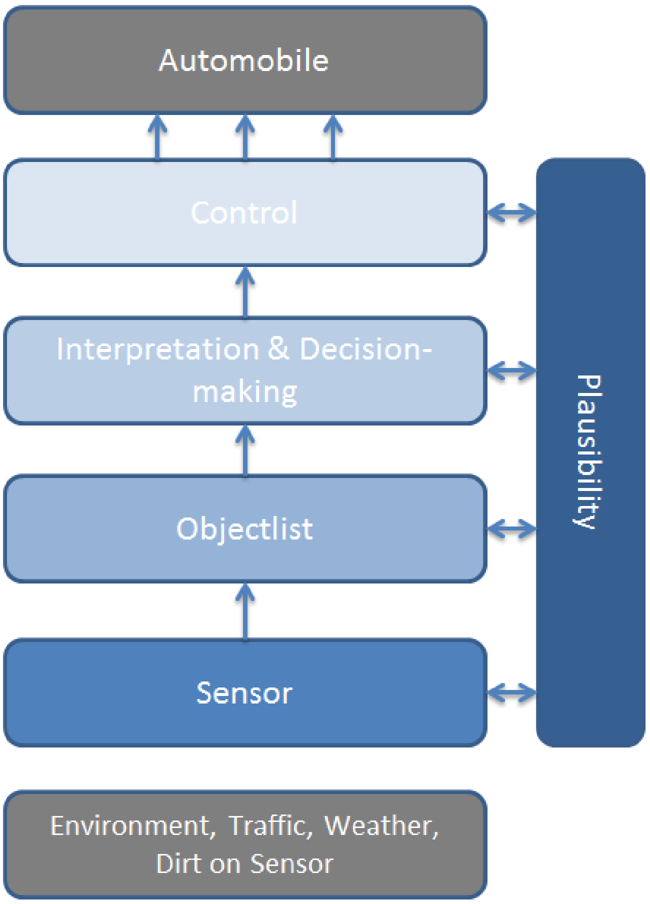
L3 Highly automated

The system takes over one or more parts of the driving task, in case of a take-over request the driver must take-over control within a certain time buffer.

L4 Fully automated

The system takes over one or more parts of the driving task and in the case of an unanswered take over request the system returns to the minimal risk condition itself.

2.4 Information Flow based Approach



Just as humans can have the same way of processing information despite exhibiting very different beliefs and behaviors, assistance systems can be set up to perform different behaviors but share a common flow of information.

Sensor

The sensor level gathers properties about the environment. On this level it is important to know how accurate the data is.

Object Lists

The measurements are collected and associated with objects. These objects are traced through time and their future paths as well as their likelihood of existence are calculated.

Interpretation and Decision Making

Based on the position and predicted path of relevant surrounding objects the situation is identified and based on this identification decisions for control are made.

Control

Control is the regulation of actuators in the car to keep the actual variables as close as possible to the target values set by the decision level.

Although they share their flow of information the amount of levels and the style of processing may vary. As this is an important part of testing great effort, despite their differences, is necessary to specifically define criteria and test situations for each device under test. In this document the sensors used for perception will be mentioned. The lower levels of information processing are addressed together with environment sensing systems in chapter 3.

2.5 Current Driver Assistance Systems

2.5.1 Sight Enhancing Systems

2.5.1.1 Assistance Demand

The driver's perceptive abilities are impaired if visibility is reduced. This happens during night, fog, heavy rain, blinding sunlight and through blinding headlights at night increasing the risk for accidents. While night accidents have been steadily declining [9] they still comprise 41% of deaths and 32% of heavy injuries compared to total injuries per year.

2.5.1.2 Assistance Goal

As implied by their name the goal of sight enhancing systems is to improve the driver's perception.

2.5.1.3 Functional Task

There are several systems which aim to achieve this goal:

- Assisting Light Distribution
- Adaptive Light Distribution
- Night Vision Systems

Collision warning systems which also include the improvement of driver's perception will be discussed separately in chapter 2.5.4.

a Assisting Light Distribution

The functional task of assisting light distribution is to change the light density distribution of dimmed and upper lights according to four environments for which different light settings have been defined. These are city, autobahn, country road and upper lights. Curve light is also attributed to assisting light distribution [1].

As its name suggests assisting light distribution is within the lowest level of automation – L1. These features are achievable with information available within the car, but if available, environment sensors can be used to improve functionality.

b Adaptive Light Distribution

The functional task of adaptive light distribution is to change the light density distribution according to the general environment (as assisting light distribution) and also according to other traffic participants and obstacles such as deer.

A marking light is used to highlight obstacles such as deer with additional light density. The lower and upper beam range is adapted in order to ensure oncoming traffic is not blinded whilst maximizing the sight distance.

These features require sensors which measure the relevant surroundings with enough spatial and temporal resolution to allow for object recognition and tracking [1]. Also light sources which allow for dynamic changes in light distribution are required. As environment sensors cameras, Lidar, Radar, range imager and night vision systems are qualified. For this system automation level L1 applies as well.

c Night Vision Systems

The functional task of night vision systems is to extend the perception capabilities of the driver by using sensors which can gather more information than the human eye [10]. This information is then either displayed to the driver or used to draw the driver's attention to a relevant object. Night vision systems are based on Near Infrared (NIR) or Far Infrared (FIR) and have a larger vision range than the human eye. They are also belong to the automation level L1 category.

FIR

The Far Infrared system is a passive system which measures the heat radiation of objects at wavelengths between 8µm and 12µm. As this radiation is blocked by glass and most other solids, these systems are quite expensive and the representation on a display does not resemble what objects in visible light look like.

NIR

The NIR systems are called near infrared because the measured wavelengths are close to the visible light spectrum between 800 and 1100nm [10]. NIR systems are active systems that send a beam of infrared waves out and detect what is reflected back. Pictures measured with these systems are very similar to what objects in visible light look like. The disadvantage of their proximity to light is that the power of the measurement beam is restricted to prevent any danger to human eyes.

2.5.2 Parking Assistance

2.5.2.1 Assistance Demand

Due to aerodynamics and other factors most cars end up with a slight chock shape. Because of this the closest line to the ground is 8–10m behind the car. This limits transversal view whilst driving backwards and poses a problem which is perceived as discomfort in regard to trajectory planning and control [10].

2.5.2.2 Assistance Goal

Parking assistants aim to increase driver comfort by easing decision making and perception as well as trajectory planning.

2.5.2.3 Functional Task

The functional task of parking assistance systems (PAS) is intertwined with their level of automation. A variety of parking assistants already exist which fulfill the assistance goals to different extents:

- Purely informational parking assistance
- Guided parking assistance
- Semi-automatic parking (transversal automation)
- Fully automatic parking (transversal and longitudinal automation)
- Fully automatic parking with automatic parking spot search

a Purely Informational Parking Assistance

The functional task of purely informational parking assistance is to provide the driver with additional visual and/or distance information without any advanced information processing. The data from a camera and or ultrasonic sensors is communicated to the driver. Automation level L1 applies. The used sensors are camera and ultrasonic.

b Guided Parking Assistance

The functional task of guided parking assistance is to provide the driver with visual and distance information as well as providing help for trajectory planning. The system is aware of the position of the car and of relevant objects and uses this knowledge to show the driver the current car trajectory as well as the optimum trajectory. The trajectory is either drawn into the camera video or into an abstract scenery. Automation level L1 applies. Used sensors are near Radar, range imager, ultrasonic sensors and cameras.

c Semi-Automatic Parking (Transversal Automation)

The functional task of semi automatic parking builds on its predecessor by performing the trajectory planning task. In this case the calculated optimum trajectory is acted upon by the assistance system. The longitudinal driving is assisted through directions. This assistance system takes over a part of the driving task and is therefore partly automated – L2. The used sensors are the same as previous but in addition a steering angle sensor and actuators are required.

d Fully Automatic Parking (Transversal and Longitudinal Automation)

The functional task of automatic parking builds upon its prior level of automation by also taking up the longitudinal task. Depending on the version the driver has to press a button in order for the system to proceed. Whether the driver has to press a button in order for the system to proceed or not, determines if the system is fully automated – L4 or highly automated – L3. The sensors and actuators used for this system are the same as for previous systems, but with each level of automation additional sensor signal quality and improved plausibility checks are required. Systems on this level must use multiple sensor types to ensure correct function.

e Fully Automatic Parking with Automatic Parking Spot Search

Basically this is an autonomous parking system with autonomous driving. The parking system has further increased requirements for parking spot detection. The autonomous driving could, if function is limited to the same parking area, work without the full requirements of autonomous driving.

Fully automated parking as well as automatic parking spot search are not yet on the market but are already being developed in research [1].

2.5.3 Active Cruise Control

2.5.3.1 Assistance Demand

Active cruise control (ACC) shares its assistance demand with common cruise control systems: Driving long distances whilst keeping a constant speed is strenuous.

2.5.3.2 Assistance Goal

The goal of cruise control is to increase driver comfort. Active cruise control has been designed to satisfy this demand to a greater extent than cruise control.

2.5.3.3 Functional Task

The functional task of active cruise control includes the capabilities of cruise control and also allows following a vehicle at a set distance from speed zero (traffic jam) up to the set cruise velocity. Active cruise control only influences the longitudinal aspect of the driving task and only performs a part of this task. It is designed to require human intervention on a regular basis to prevent a false feeling of safety. Due to that ACC falls into automation level L2. The used sensors are Radar, Lidar and ultrasound (in traffic jams). Because the ACC influences acceleration as well as breaking it has to interact with most of the control units in the power train. Ensuring that this interaction is failure safe is subject to extensive testing.

2.5.4 Front Collision Mitigation (Avoidance) Systems

2.5.4.1 Assistance Demand

The demand for front collision mitigation systems is safety. The driver's capability to react to foreseeable dangerous situations varies [1]. Attention can be bound by something non-driving task related, visibility of the danger source can be reduced and in the case of "looked but failed to see" hazard recognition simply fails. In these situations there is a clear need for front collision mitigation systems.

2.5.4.2 Assistance Goal

The goal of collision mitigation systems is to reduce the driver's reaction time to dangers and in the absence of human reaction to take over longitudinal and in some cases longitudinal as well as transversal steering.

2.5.4.3 Functional Task

The functional task of front collision mitigation systems is to detect objects on a collision path and to warn the driver with sound and haptic signals, e.g. by vibrating the steering wheel. As soon as an object on collision path is detected the car is prepared for impact. This includes preloading the breaking system as well as tightening the safety belts. If no reaction follows, further behavior depends on the automation level of the ADAS. There are systems which have been tailored to meet automation level L2 and will only start breaking when impact is unavoidable in order to reduce the severity of impact. There are systems in development which initiate breaking at an earlier point in order to avoid impact altogether. These systems also take over transversal control for this time and are therefore in the automation level L4 category. In most European countries such autonomous breaking systems will only be possible, if the currently valid law according to the Convention on Traffic Roads (Wiener Übereinkommen über den Straßenverkehr) [11] is modified. This treaty states that every vehicle must have a driver which must be a person and that this driver must always be able to control the vehicle. Another situation in which front collision avoidance systems can take action is when a pedestrian unexpectedly enters the driving trajectory. In this case the L4 system takes over longitudinal and transversal control to evade the pedestrian. The ADAS can outperform humans in this scenario by distinctively controlling the brakes via EPS to guide the car along a trajectory which would otherwise be hard to follow. Front collision systems use environment sensors such as Radar, Lidar, range imager and cameras.

2.5.5 Lane Departure Warning and Lane Keeping Support

2.5.5.1 Assistance Demand

Keeping a car within a given lane is mainly a safety concern. The demand for such a function can be drawn from traffic accident statistics. Over a third of all fatal road accidents results from lane changes or unwanted lane departures which indicates a clear demand for a system aiming at the prevention of such accidents [1]. There are several systems which interact with the driver’s task to steer.

2.5.5.2 Assistance Goal

The safety goal of lane keeping assistance systems is to reduce the risk of unwanted lane departures. Furthermore the comfort goal of lane keeping assistance is to make transversal steering less challenging.

2.5.5.3 Functional Task

The functional task of lane keeping support is to apply an additional moment onto the steering wheel in order to keep the car in the middle of the driving lane. This can be configured in order to provide comfort or to only be activated before an impending unwanted lane departure.

The functional task of departure warning/prevention is to warn the diver of an impending unwanted lane departure and, in the case of prevention, to steer the car back onto the driving lane, if the driver shows no reaction. This can be achieved for example through ESP breaking.

Combinations of the above presented functional tasks are also possible. With a single functional task these systems do not exceed automation level L2. For lane keeping with steering and breaking capabilities automation level L3 or L4 applies.

In order for these systems to function properly the driver's intention recognition is very important, "unwanted lane departure" needs to be discerned from "wanted lane departure". The driver's intention recognition gains further predictability, if data from vigilance detection is available. An optical system is required to sense and recognize the driving lane. Mainly cameras provide the lane perception capabilities, but some Lidar and range imager systems can also be used.

2.5.6 Lane Change Assistance

2.5.6.1 Assistance Demand

According to the German In-Depth Accident Study (GIDAS) between 1985 and 1999 [12] on average 5% of all accidents occurred during a lane change maneuver. These statistics provide the motivation to design a system which may help to decrease this amount and to improve safety.

2.5.6.2 Assistance Goal

The goal of lane change assistants is to warn or to prevent lane changes in dangerous situations.

2.5.6.3 Functional Task

The functional task of lane change assistants is to perceive the relevant surrounding for a lane change/–overtake maneuver and to issue warning signals or to prevent a lane change, if the intended action is dangerous. This function exists to different extents. Systems which only warn the driver are part of automation level L1 and systems which actively take over part of the driving task can be designed to be part of automation level L2–L4. This task requires sensors which monitor the blind spot on each side of the car. Also, oncoming traffic needs to be recognized. Fast approaching traffic from the rear side and driver intention monitoring systems improve the functionality of this system. For such a system cameras, and mostly Radar but also Lidar or range imagers are used.

2.5.7 Junction Assistance

2.5.7.1 Assistance Demand

Again, junction assistance serves the need for further safety. Mastering junction assistance will be key for autonomous driving. Junctions are information dense environments where correct interpretation of the situation and recognition of all relevant factors is at times hard to achieve. Due to the complexity of a junction, assistance is split into different scenarios. In each of these scenarios drivers are at times subject to perception or interpretation errors which lead to flawed decisions. Typical errors include the misinterpretation of the velocity of other traffic participants.

2.5.7.2 Assistance Goal

The goal of junction assistance is to improve decision making and information availability for drivers. In order for the assistance functions to be an improvement they have to excel at handling the “Warning Dilemma” [1]. This is the tradeoff between warning at the latest possible time and the expectable amount of false warnings. Due to the multiplicity of situations and driver behavior which will differ from regulations if a situation allows, mastering the “Warning Dilemma” is the most important obstacle to overcome for these functions to find good acceptance.

2.5.7.3 Functional Task

The functional tasks will be discussed separately. Junction assistance consists of:

- Stop sign assistance
- Traffic light assistance
- Entering or crossing a junction assistance
- Left turn assistance

Stop Sign Assistance

The functional task of Stop sign assistance is to prevent unwanted rolling over the stopping line by bringing the car to a standstill right at the stopping line. This system only acts, if it interprets stopping as the driver's intention, but does not so if the driver plans only on significantly reducing his speed.

Traffic Light Assistance

In traffic light assistance two cases are the main source of accidents: Transversal traffic accidents, which are usually happening due to red light violation, and rear-shunt accidents. The functional task of traffic light assistance is to warn, if red light violations are impending and to support the starting of traffic after a red phase.

Entering or Crossing a Junction

In this case the driver only has to stop if transversal traffic is present. The functional task for entering or crossing a junction is to detect, whether transversal traffic is present or not and to issue warning signals and/or to prevent the car from entering or crossing. The assistance system needs information about the transversal traffic to support the driver whilst approaching the junction.

Left turn Assistance

This system aims to help the driver when leaving a road with a left turn. Despite the multitude of left turn accidents the most important one is where the left turning car crashes with oncoming traffic. The functional task of left turn assistance is to detect oncoming traffic and warn the driver, if the maneuver is dangerous.

With sensors and information gathering of the environment only from within the car, junction assistance has to face a tradeoff between safety and convenience. Assisted and autonomous cars need additional time, e.g. right at the junction to sense whether transversal traffic is oncoming or not. Due to this Car to Car (C2C) and Car to Infrastructure (C2I) are viable options to achieve both safety and comfort. Right now in Europe Car to Car and Car to Infrastructure systems are only subject to research. In Japan a C2I system – the Vehicle Information and Communication System (VICS) was implemented nationwide in 2003. C2C and C2I will be discussed in the outlook on future ADAS. Also future sensor systems might be capable of providing junction assistance functionality without a tradeoff between safety and convenience (speed). For all these assistance functions driver intention recognition is very important and can be improved by driver monitoring systems. Separate functions can be implemented on an automation level of L1 and L2, but full capability requires automation level L3 and L4.

2.6 Select Topics on the Future of Assistance Systems

The development of assistance systems serves to increase safety and comfort by optimizing the capabilities of the car-driver-system and by improving assistance systems themselves to the point where they are able to take over parts of the driving task.

These two trends will lead to safer traffic and, if enough parts of the driving task are mastered, to autonomous driving. Every system profits from further information about the environment and the driver. Due to that sensor fusion, where the information of all environment sensors is gathered, merged and made available for all assistance systems, will become the dominant form of information processing. At the point where a significant portion (over 5%) of the traffic is equipped with advanced driving assistance systems communication between cars and between cars and infrastructure can serve as an additional performance boost for assistance systems. The redundancy requirements for autonomous driving could be met a lot easier, if every car was equipped with a unit which broadcasts its current position and velocity. Interconnecting the traffic participants may also help to improve overall traffic flow. These promises drive the motivation to develop such systems.

2.6.1 Car to Car (C2C) and Car to Infrastructure Communication (C2I)

Radio is the current main technology over which Information about traffic flow and unusual dangers such as wrong-way drivers is transmitted. Car to Car and Car to Infrastructure communication will allow more information to be transmitted in a more specific way [13]. The possible applications are numerous, for example traffic lights could transmit the remaining duration of their green phase which would allow ADAS to give more specific recommendations about the velocity to approach the lights. Also traffic monitoring systems at junctions could deliver the required information about transversal traffic to Junction Assistance. With C2C communication platooning, where cars are grouped together at one velocity and drive with less distance between them acting as a single entity and harnessing the fuel savings of reduced air resistance, becomes possible. Information about accidents, traffic jams and construction sites could be transmitted immediately after formation and data about the time delay caused by a traffic jam would be available firsthand. Assistance Systems such as Blind Spot Detection and Lane Change Assistance would gain reliability. Traffic jams without accidents or construction sites occur at speeds over 85km/h and above a certain occupancy rate of a highway. These jams form due to large velocity disparities and over-reactive breaking. Car to Car communication may allow Assistance Systems to reduce this effect and thus increase the maximum throughput of highway systems.

2.6.2 Autonomous Driving

With improving performance at falling costs for sensors and computing power combined and with the ongoing electrification of formerly mechanical systems, such as e-brakes and e-steering, autonomous driving has come within the range of feasibility. Unprecedented speed in the development of new assistance systems with growing functionality and increasing numbers of proof of concept autonomous cars make the question about autonomous driving about when, rather than about whether they are possible or not.

Autonomous driving offers the promise of reduced fatal road accidents, increased traffic throughput and improved individual mobility despite any disability. There are still obstacles to overcome in order to make autonomous driving a reality.

Assistance systems already require additional operational skills. The driver needs to know which state the assistance systems are currently in – this is called mode awareness. Furthermore, he needs to know how the assistance system signals information and how it behaves in any situation. In addition, if an advanced assistance system issues a takeover request, the driver needs to know in which situation he is in, otherwise he will not be able to perform the best choice of actions. For autonomous systems which allow for different degrees of automation and for pre-stages in which they are only able to operate autonomously in parts of the traffic, network concepts allowing the driver to easily predict the behavior of the autonomous system will be necessary. Any driver encountering an autonomous car will face the same problems. In order to ensure wide acceptance, concepts to make autonomous cars easily predictable for other traffic participants will be required.

Currently, autonomous cars cannot be licensed due to law. Also the question of liability for accidents has not been answered. Even if the “Wiener Übereinkommen” is modified and liability is regulated similarly to the aviation industry any autonomous system may not increase risk for any traffic participant group. Providing proof for that will be difficult. An Autonomous System would at least have to show that the amount of severe accidents is lower than the best relevant comparison group. On German highways e.g. every 5 million kilometers one severe accident happens. With an expectation of risk reduction of 5% this would require 100 million kilometers to reach 5% significance as also stated by Winner and Wachenfeld: "*Recent scientific publications predict that **more than 100 Mio km of road driving are required** for fully automatic vehicle release"* [18]. This alone would cost hundreds of millions of euros and any change in the autonomous system would require the same test again [1]. This makes clear that new testing methods will need to be developed which have the capability to test performance without blowing up cost. A test system capable of simulating real driving environments to a sufficient extent may be a key ingredient to the solution for this problem.

Autonomous driving will evolve from current assistance systems step by step. The first autonomous system will be capable of handling the highway environment. After sufficient development of overtake assistance, junction assistance and obstacle evasion autonomous land road systems will become possible. The last step will involve handling the urban environment.

With increasing capabilities any test system will also need to evolve. There will have to be a large library of test cases to simulate all relevant situations. Traffic simulation and validation methods will be required in order to ensure the test system resembles reality enough to test real performance. Sensor stimulation will need to improve with environment sensor capabilities. Lastly, the requirements for a test system might change along the development process of autonomous systems. The market will therefore need to be closely monitored in order to react to future requirements in advance.

3 Environment Sensors for ADAS Functions

Each sensor system for ADAS functions has been subject to a long research and development process. As a result, there are great complexity and variety within these systems. The following chapter gives an overview of commonly used principles.

3.1 Ultrasonic Sensors

Ultrasonic sensors are used to measure distances. While distances can, among others, be measured trough lasers, Radar, or through capacitance, sealed piezoelectric ultrasonic sensors are the de facto standard for parking assistance systems. To keep this document dense with relevant information only the piezoelectric sensor principle will be discussed.

3.1.1 Physical Measurement Principle

At the heart of an ultrasonic sensor lies a piezoelectric crystal. This crystal can convert electrical energy to mechanical energy and vice versa through the piezoelectric effect [20]. This effect occurs in crystals where the arrangement of atoms in their lattice is such that the charges in the lattice are distributed asymmetrically which creates an electric dipole potential. These dipole potentials build domains of uniform polarization. By applying a strong electric field the polarization of these domains can be aligned. A deformation of the lattice in the direction of the dipole potential will then generate a voltage proportional to the amount of deformation [1]. In turn, applying voltage to the crystal causes the lattice structure to deform accordingly. This property can be used to generate or receive mechanical oscillations. In the case of automotive ultrasonic sensors the oscillations have a frequency between 40 kHz and 50 kHz. The mechanical deformation of the crystal is too weak to generate a strong coupling between air and the crystal. A membrane is used to amplify the effect at the resonant frequency. In the automotive industry metal membranes are used to increase durability. Due to the metal membrane Ultrasonic sensors require driving voltages of up to 160V. The sound wave which is generated by the sensor radiates outward until it hits another surface of which it is reflected. Due to the low density of air in relation to solids the reflection is very close to a total reflection. The receding sound wave sets the sensor into motion again which in turn causes a detectable electric signal.

3.1.2 Information Flow and Processing

Signal generation and detection are performed with hardware. After an echo is detected the distance of the respective object is determined by the time it took the sound wave to travel to the object and back. Systems which use one sending sensor and multiple receiving sensors can improve the accuracy of the system by applying triangulation with respect to the spatial positions of the receiving sensors; this is called cross-detection. The calculated distances are checked for plausibility and multiple measurements are made in order to get information about distance as well as velocity.

3.1.3 Measurement Errors

Sound travels at different speeds through air according to humidity, temperature and air pressure. The accuracy of distance calculation depends on how accurate these parameters are measured and compensated. The reflectiveness of objects to detect depends on their geometry: planes normal to the expanding ultrasonic wave reflect the best, planes in a 45 degree angle to the sensor reflect the worst. Due to the large difference in density between air and solids ultrasonic waves are mostly reflected totally; only vegetation and clothing reflect less. The wheel house can generate multiple false echoes. Systems without cross-detection will detect the same distance for all objects lying on the surface of a sphere with the detected distance. This can lead to false errors and it limits the accuracy as the desired variable is the closest distance between car and object.

3.1.4 Implications for a Stimulation System

For ultrasonic sensors an external stimulation without changes in the measurement system is achievable. Due to the slow propagation of sound waves in the air the constraints for the stimulation system can be met with currently available equipment as demonstrated in chapter 5.

3.2 Radar

Radar was first developed for military use and has recently become cheap and compact enough for use in cars. Radar systems measure distance and speed with high accuracy. Their spatial information is less accurate. Radar antennas can be set up in various different ways to measure the angular position of objects in elevation (horizontal angle) and azimuthal (vertical angle) direction. The advantage of Radar over other distance measurement systems is that while distance is measured through time of flight and/or triangulation, speed is measured via the Doppler Effect. Radar uses electromagnetic waves with a frequency between 300 MHz and 100 GHz. For use in the automotive sector four frequency bands are currently available (24.0–24.25 GHz, 76–77 GHz, 77–81 GHz and 21.65–26.65 GHz) [15].

3.2.1 Physical Measurement Principle

Radar systems send out electromagnetic waves and measure the receding waves. A local oscillator is used to generate the desired frequency which is then emitted through antennas. The shape of the antenna determines which shape the Radar beam has. Focused beams with widths between 4° and 30° are currently possible [1]. When the Radar signal hits an object and is reflected it undergoes a Doppler Shift proportional to the relative speed between Radar sensor and object. The measured signal echo is then measured and the distance and speed of the detected objects are determined.

3.2.1.1 Radar Cross Section (RCS)

The RCS describes how much an object reflects back in terms of a sphere with radius a. A product of the RCS with the squared wavelength $\sigma\lambda^2$ describes how much of a homogenous incoming radar wave is reflected in a spatial angle. The unit of the Radar Cross Section is m^2 and relevant objects on the street have RCS ranging from 1 to 10,000m^2. This leads to high constraints on the dynamic of the detection path.

3.2.1.2 Distance Measurement

Distance is mainly measured by time of flight. Unlike ultrasonic distance measurement, Radar systems rely on sophisticated signal processing. To properly describe this signal processing would exceed the scope of this thesis. The techniques used include Frequency Shift Keying (FSK), Linear Frequency Modulation Shift Keying (LFMCW/FMSK/FSK), Frequency Modulated Continuous Wave (FMCW) and Chirp Sequence Modulation.

For systems with multiple detection antennas triangulation in combination with multipath discrimination methods improve the measurement.

3.2.1.3 Doppler Effect

Christian Doppler predicted in 1848 that electromagnetic waves are subject to frequency shifts according to relative speed. Moving towards or away from the source of a wave will shift the perceived frequency. This shift is proportional to the relative speed between source and observer and also proportional to the reciprocal value of the frequency's wavelength $\frac{f_0}{c}$. With c being the speed of light and r the distance between the radar system and the reflecting object:

$$f_{Doppler} = -\frac{2\dot{r}}{\lambda} = -\frac{2\dot{r}f_0}{c} \qquad (3\text{-}1)$$

At a carrier frequency of 24 GHz a relative speed of -90m/s = 324 km/h (oncoming traffic) would lead to a Doppler Shift of:

$$f_{Doppler} = -\frac{2\dot{r}f_0}{c} = -\frac{2 * 90\frac{m}{s} * 24\,GHz}{299792458\frac{m}{s}} = 14{,}4kHz \qquad (3\text{-}2)$$

Although also present in the carrier frequency the Doppler Effect only leads to a frequency change of a millionth here. The effect becomes well measurable through the lower frequency of the measurement signal modulated onto the carrier frequency.

3.2.1.4 Angular Measurement

For most Angular Measurement principles a narrow beam is required for high angular resolution. The shape of the radiated wave depends on the shape of the antenna. The radiated frequency and the shape of the antenna interact to form radiation densities which are similar to those of an interference pattern, in which the power is spatially distributed in areas with maxima and minima. The main maxima in the center is called the main lobe, all other maxima are “side lobes” as shown in Figure 3-1.

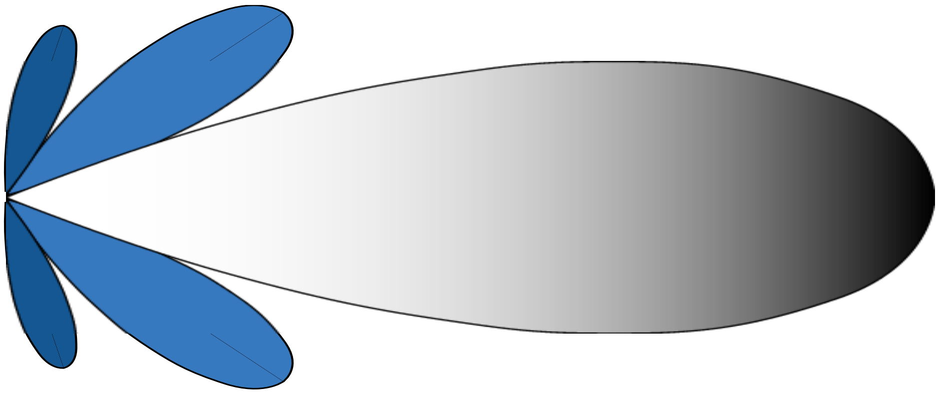


Figure 3-1 Main Lobe in Grey, Side Lobes in Blue

The smaller the width of the main lobe the higher is the spatial resolution. Current systems have a static angular resolution between 2° and 0.1°. Even a main lobe taking up only 2° in azimuthal direction will have a width of ~7m at a distance of 200m. This is calculated by

$$\frac{w}{2} = d * tan(1°) => w = 2 * 200m * 0{,}01745 = 6{,}98m \qquad (3\text{-}3)$$

Several approaches have been developed to deal with this circumstance. Although elevation measurement would also be desirable, current systems cannot achieve the necessary accuracy and are therefore not designed to gather elevation information.

3.2.1.5 Scanning

With the scanning method the antenna or the lens (Radome) in front of the antenna diverts the beam to scan over the field of view during a measurement cycle. Any object within range will lead to a detection peak at its angular position.

3.2.1.6 Monopulse

In a monopulse measurement system typically one antenna is used to generate a signal and two antennas with different azimuthal characteristics and or separate positions are used to measure the reflection. From the incoming signal a sum and a difference are generated. By building the quotient of those two the angular position of an object can be determined. This measurement is compromised if two or more objects are measured simultaneously. Therefore this measurement system requires good distance and/or relative speed discrimination to avoid errors and mistaking multiple targets for a single one.

3.2.1.7 Mulitbeam

Multibeam is an improvement of the monopulse measurement system. Due to additional antennas a larger azimuthal observation angle is possible. Multitarget discrimination becomes easier as well.

3.2.1.8 Other Developments

There are systems which use the first side lobe to increase the azimuthal measurement angle for short distances.

3.2.2 Information Flow and Processing

Despite the multitude of different approaches information processing follows a similar sequence.

The first step is signal generation. This includes modulation of the carrier with the measurement signal and spatial beam shaping. The detected signal is demodulated, amplified and digitized. The digital signal undergoes a Fourier transform where the complex amplitude and frequency provide information about distance, speed and azimuthal angle. The frequency spectrum is analyzed to detect peaks. These peaks are then matched to correlate them to an object. Additional signal processing extracts the azimuthal information from the amplitudes and the antenna characteristics. The detections which are likely to fit together are merged to one object. The last step is tracking. Here the objects measured in the past and their current positions based on trajectories are compared to the newly detected objects. After a filtering mechanism which estimates the likelihood of whether objects exist or not and where their current position is, a prediction for their future position is made.

3.2.3 Measurement Errors

Environmental factors can influence the quality of measurements. Rain raises the noise level and water spouts can lead to ghost detections. The increased noise level decreases the Signal/Noise Ratio (SNR) and with that the maximum range of the Radar system. An inhomogeneous water film on the surface of the Radome can diffract mm waves to a large degree and degrade azimuthal resolution. Metallic varnish cannot be used on Radomes as it changes the shape of the beam. Additional coatings of regular varnish can also pose a problem. Metallic layers significantly thinner than the penetration depth (<1µm) can become transparent to mm waves while maintaining their properties towards visible light. In general any contamination of the Radome by e.g. ice, snow or dirt may lead to measurement degradation. Some Radar systems have a heating system and a separate wiper to maintain working conditions for the Radar system. Additional sources of systematic errors are azimuthal and elevation mounting errors. Some systems provide calibration methods to reduce or adapt the system to these errors.

On the information processing side multipath propagation, standing objects and multiple targets pose error sources. In addition to these, typical sensor errors for distance, velocity and azimuthal angle apply.

3.2.4 Implications for a Stimulation System

Stimulation for Radar is achieved easiest on the object level. Due to the multitude of physical implementations, signal processing techniques and used frequency spectra it is likely that no single stimulation system is possible for all systems.

In order to achieve a complete physical stimulation system four different frequency bands would have to be mastered. An angular resolution of 0.1° would be required. Further thought will need to go into requirements regarding the shape of the radiation and arrangement of antennas. In order to simulate mountain and valley scenarios the system should be capable of elevation changes by roughly $\pm 10\%$. A sophisticated signal generation unit is required to generate signals which resemble a Doppler Shift and to replicate the various different approaches to signal generation. Along with the challenges to signal generation synchronization seems to be the biggest problem. Electromagnetic Radar waves in the air propagate nearly at the speed of light. For the stimulation system to be fast enough to mimic a radar echo it has to be prepared to generate the desired signal and only be triggered by the measurement pulse. The delay between trigger and signal generation is set by the simulation according to the desired object distance, but must be stored in a part of the circuit. Some of the Radar systems emit a continuous Radar wave onto which during a measurement cycle the measurement signal is modulated. In this case a demodulation as it is performed within the Radar system would take too much time. It is possible that a circuit built solely to detect whether an impulse has been sent or not might suffice to time constraints. As signal generation is under such tight timing constraints the detection should have a separate antenna. For short distances instead of signal generation, analog modification of the measurement signal and delay according to the desired distance might be the only possible implementation.

The time delay between new calculations by the environment simulation and their update to the stimulation system should not exceed several milliseconds. It is unlikely that with current computing capacity any full scale simulation of radiation propagation would be fast enough to serve as basis of the stimulation. Due to that only a behavioral stimulation is feasible. Behavioral stimulation means that a model is built which predicts what a Radar system would measure based on generalizations of the system. If the software model is sufficient there is no significant difference in any criteria and in any test between the model and a real Radar system. The stimulation would then extend this model by stimulating the real radar system in such a way that there is no significant difference in any criteria in any test between the real test situation and the simulated test situation.

3.3 Lidar

Light Detection and Ranging (Lidar) systems resemble Radar systems where the electromagnetic waves used are in the near infrared with 800 to 1000nm wavelength instead of the micrometer range. LIDAR is superior to RADAR in terms of azimuthal discrimination as a resolution in the cm range is possible [10]. This advantage is opposed by two disadvantages. Since the frequencies used are so close to visible light Lidar systems have to fulfill laser safety regulations. For Lidar systems laser safety class 1 applies. These systems are designed to ensure that the human eye cannot be harmed by any amount of exposure to the system which limits the maximum energy of Lidar. The second disadvantage is the systems susceptibility to weather conditions. Fog and heavy rain significantly decrease range. This poses a problem if Lidar is used for safety functions.

3.3.1 Physical Measurement Principle

For Lidar Near Infrared (NIR) electromagnetic waves are used. Due to the high frequency this technology does not require large antennas. High-power light emitting diodes are used to generate the beam. The light emitting diode has the structure of a laser to generate a highly focused light beam. This light beam propagates though air, is reflected and is then detected by a light detecting diode. For light propagating across two different media three factors come into play: attenuation, diffraction and reflection. As light travels through the air a part is reflected by elements within the atmosphere as water or dust particles, an additional part is absorbed. As the light hits an object only a part of it is reflected. Depending on how focused the beam is the light is either reflected in a wide angle or narrowly. Highly focused beams have the disadvantage that they can be reflected away from the sensor. The light detecting diode is operated with a large pre-resistor and in reverse. Due to the high field strength a single photon is enough to cause an avalanche. The large resistor prevents the diode from remaining in reverse conducting mode. This process is self-perpetuating and allows for measurement frequencies of up to 100 MHz [1].

3.3.1.1 Distance Measurement

Lidar is a time of flight measurement system. Due to its high frequency modulation of a carrier frequency with a measurement signal is not possible. Therefore the carrier signal has to be modulated. Rectangular, sine and pulse -modulation would be feasible. Due to the limitations on emitted energy pulse modulation is used in most Lidar systems. In order to achieve a high spatial resolution the pulses should be as short as possible. With pulse durations on the magnitude of nanoseconds a typical pulse takes up about 1m.

3.3.1.2 Velocity and Acceleration

The Doppler Effect could theoretically be used to determine relative speed. Due to the limitations in frequency modulation this effect cannot be harnessed currently. Thus, velocity and acceleration are determined by differentiation. This is possible without large errors because of the high spatial resolution and measurement speed of Lidar.

3.3.1.3 Scanning

Scanning is one of two main principles to gain azimuthal and elevation information. This technique uses a lens or mirror to guide the beam through the field of measurement. Mechanical scanning works best for single beam systems.

3.3.1.4 Multibeam

In multibeam systems, as the name suggests, spatial information is gained by using multiple signal transmission units.

Combinations of the two techniques are also possible. An advantage of a multibeam sweep is that whilst simultaneously gaining a large amount of information, by scanning the azimuthal size of objects can be estimated. This is viable information for object tracking and assistance systems.

3.3.2 Information Flow and Processing

As the length of a single pulse is around 1m further signal processing is required to improve accuracy. The detected signal is filtered, amplified and digitally stored in the form of range gates. These range gates correspond roughly to the size of an impulse. By addition of multiple pulse detections measured distances in range gates resemble a Gauss curve. By reconstructing the peak of that curve spatial resolution within the cm range is possible. The accuracy of the system can be adjusted by the amount of pulses per measurement cycle. If accounted for Lidar is also capable of multi-target-tracking.

After a measurement cycle the peaks in the range gate register are related to objects. Velocity, acceleration, azimuthal and elevation are attributed to these objects.
The position of these objects is then compared to the predicted position of objects detected in the past. A Kalman filter is used to incorporate the newly measured information into past measurement events. The current most likely position of objects is calculated and their position during the next measurement cycle is predicted. This information constitutes the output of Lidar systems.

3.3.3 Measurement Errors

As discussed in the beginning of this chapter, Lidar is strongly influenced by weather conditions. Rain, snow, fog decrease the range of the system, also any dirt on the cover limits function. Due to the reflection off of these disturbances Lidar is capable of detecting whether it is compromised or not. This allows Lidar to be used to determine how visibility for the driver is. The detection path of the Lidar system requires a great dynamic range as the sun emits infrared light in much greater quantities than the Lidar system. There are very efficient techniques to filter the sunlight out, and also allow the Lidar system to detect whether it is day or night. For highly focused Lidar systems total reflection is a source of possible measurement errors.

Due to their high spatial resolution modern Lidar systems are capable of tracking up to 20 objects on and off the street. How the Kalman-filter is adjusted greatly determines how accurate and error-prone the Lidar system is.

3.3.4 Implications for a Stimulation System

Due to the large variety of Lidar systems stimulation on the object level is the most feasible. Again a complete simulation of the measurement cycle and an according stimulation surpasses the available time budget. If a physical stimulation system were to be designed either a huge array of Laser diodes or multiple micro-electromechanical mirrors in combination with a constant Laser source could be used to emulate the infrared echoes. This time due to the limitations in signal modulation, synchronization might be easier to achieve and a proper detection system should be easier to build. The high spatial resolution and the capability of tracking up to 20 objects requires a stimulation system with a large amount of sources. Further thought will have to go into whether multiple diodes or micro-electromechanical mirrors are easier to build. The time delays between detection and stimulation would again need a place to be stored in hardware. Due to the high frequency and extremely short pulse durations reproducing the probabilistic range gate measurement cycle might pose a problem.

It is possible that the stimulation system is detected by the self-diagnosis function of the Lidar system, in which case self-diagnosis might need to be disabled on a software level.

3.4 3D Time of Flight/ Range Imager

Range imagers fulfill the function of a camera combined with a Lidar system. Each pixel measures the brightness and distance of the closest object in the line of sight. Photonic Mixing Devices (PMD) are the most prominent and promising technology for range imaging. As Lidar PMD uses near infrared light for measurement, current PMD’s, compared to cameras, have a fairly low resolution between 1024 and 65536 pixels [10]. Their low resolution is a negative consequence of their big advantage over other measurement systems: The distance is measured right at the pixel level and no processing power is required for calculation.

At this point PMDs have a tradeoff between transversal and longitudinal accuracy, the larger a pixel the better the statistical certainty and thus the higher the quality of depth information. The smaller the pixels the more lateral information the PMD can deliver. This tradeoff translates into short range versions with high transversal accuracy and mid-range systems (up to 70m) with lower transversal accuracy. For short ranges a longitudinal accuracy within mm is possible.

For short ranges, PMDs which use the regular daytime running lights as source may be possible in the future.

3.4.1 Physical Measurement Principle

Photonic mixing devices use a Laser diode to generate near infrared light. This light is then modulated at typically over 10MHz. After reflection the light enters the PMD pixel. This pixel consists of two photo gate strips between two diodes. The diodes are connected in reverse and the reverse current is a measure of the amount of photons currently being detected. The voltage applied to the two photo gates determines the direction in which electrons generated from the incoming photons take. This voltage is modulated in exactly the same way as the laser diode. Ambient light will stimulate both photo gates equally and as it has no modulation end up generating the same amount of reverse current on both diodes. The modulated light however will generate reverse currents in relation to the phase shift between itself and the outgoing light. This phase shift relates to the distance which light has travelled. Light travels at 300m/µs and therefore a modulation which is capable of discerning objects up to 150m would need a periodicity of 1µs. If the difference between the reverse currents is integrated over time, it yields a direct measure of the phase shift. Based on the continuous current generated by ambient light the Suppression of Background Illumination (SBI) adjusts the voltage in the space charge region which allows the system to keep the sensitivity high in every lighting situation. Also, the continuous current is the measure for the brightness of the pixel.

3.4.2 Information Flow and Processing

The quality of measurement of PMS's as with other light based measurement systems relies on statistical certainty. Current systems provide an output of 100 measurements per second. Each measurement consists of multiple measurement cycles. Due to the layout of the PMD each measurement also provides a measure for the Signal/Noise Ratio in the measurement by comparing the amplitude of the alternating reverse current (measure for the detected active light) to the amount of continuous current (measure for ambient light). The information processing consists of calculating the statistically most probable distance, then grouping pixels together to objects which are then tracked.

3.4.3 Measurement Errors

The biggest source of error is the shot noise from sunlight. In general any environmental factor which decreases visibility also impairs quality of measurement. Fog and rain are the most prominent threats as they reflect light at shorter distances which has a smaller phase shift and clouds the original measurement. Any dirt or ice on the cover will prevent the system from working. In this case the system is capable of recognizing whether it is functional or not. For single pixels multipath propagation and two objects at different distances within the measurement field can lead to errors. Due to the high scattering of near infrared, multipath propagation is unlikely to be a major concern.

3.4.4 Implications for a Stimulation System

As with other advanced measurement systems stimulation on the object level would be the easiest to build. If a physical stimulation were to be designed the continuous measurement beam used to determine the distance poses a problem to the physical design of a stimulation system because its reflection is likely to be detected by the PMD. Also the high spatial resolution limits the feasibility of distinct stimulation sources. Given that the modulation algorithm is known a system of mirrors might be the best choice for stimulation. The source beam is directed into the stimulation device and either used to synchronize the stimulation or used directly as source for the feedback signals. This source would then be split into the required amount of signals and each be delayed by the required amount of time. This delay may either be achieved through a mirror system or by generating signals with the desired delay. Building this mechanism would be the core challenge for a stimulation system. After creating the array of beams with the required delays they would be damped to match the desired brightness by an adjustable semitransparent material. The array of beams would then have to be focused on the PMD lens by another set of microelectromechanical-mirrors.

3.5 Camera

Camera systems have undergone a constant process of improvement throughout the last years. Current systems with a monochrome 8bit VGA resolution of 640x480 pixels and 25 Hz frame rate generate a data stream of over 60 Mbit/s and with the trend going towards megapixel cameras this amount is certainly going to increase [1]. These usually contain by far the largest amount of processing power of all automotive signal processing units. This stems from their use as source of machine vision. Sophisticated multilayered processes provide object recognition and tracking information. Camera systems provide a 2D projection of their 3D field of view. Their measurement principle makes them scale-blind. Recovering the loss of depth information is one large contributor to the demand in processing power.

From all environment sensors presented camera systems are the only passive system. This is an advantage as no legislation is required to allow their integration into the automobile. Unfortunately this also means that any stimulation system will introduce some amount of delay compared to reality. Although at a rate of 25 Hz/40ms per frame it should still be possible to make stimulation significantly faster than the measurement period.

The traffic system is designed for the human eye. The great advantage of camera systems is that they are able to tap into the efforts which are undertaken to provide visual information and guidance for humans. Also, camera systems are unparalleled in their transversal accuracy.

3.5.1 Physical Measurement Principle

The two main technologies for imaging are Charge Coupled Devices (CCD) and Complementary Metal-Oxide-Semiconductors (CMOS), which are also used in the automotive sector. Both techniques take advantage of the photoelectric effect. This effect describes how a photon lifts an electron from the valence band to the conduction band, freeing it up for movement. CCDs collect all electrons generated in one pixel during a given time span and then serially measure the resulting voltage of each pixel row. CCD sensors have a higher sensitivity compared to CMOS but require more noise compensation and power.

CMOS is the leading technology for integrated circuits and has also become the dominating technology for imaging. CMOS based cameras mainly use a photoelectric diode operated in reverse. At the start of measurement the reverse voltage is set to a defined level. During measurement the capacity of the depletion region is discharged by the photoelectric current. The reverse voltage drops accordingly. The reverse voltage at the end of a measurement cycle is then amplified and digitalized.

3.5.2 Information Flow and Processing

In order to cope with the large amount of data, the images are generalized in a number of ways. First, lens errors are corrected. This allows for the following algorithms to use the model of a pinhole camera. The corrections include astigmatism, coma, vignetting and distortion.

The next level uses filters and other operations to highlight relevant characteristics of the picture. Point operations manipulate the brightness of single pixels, such as histogram broadening, equalizing and threshold procedures. Local operators calculate the new value of a pixel according to its neighbors. These operations include smoothing with Gauss or binomial filters and morphological filters. Global operators take the whole image into account for the manipulation of a single pixel, such as Fourier transform or Hough transform. Geometric operators do not change the brightness of the picture but manipulate the whole picture; those include rotation, mirroring and scaling.

After picture improvement, relevant characteristics are extracted from the picture. For higher level processing only the extracted characteristics are used. There are two types of characteristics: Single picture characteristics which analyze single frames and correspondence characteristics which analyze the change between frames. Single picture characteristics include rims and corners for which special algorithms based on gradient search are used. Correspondence characteristics analyze the change between pictures in order to detect movement and also as basis for motion-stereo 3D reconstruction.

For systems with two or more cameras a 3D reconstruction for each frame is possible. Systems with only one camera can take advantage of the motion of the camera in order to reconstruct the 3D scene. This works best with a static environment and loses accuracy with movement.

Based on these extracted characteristics object detection and tracking is possible. Two algorithms are mainly used for this purpose: Kalman filters or Bayesian particle filters. One possible application is lane marker detection.

Based on detected objects the lane detection algorithm produces predictions as to where the next objects should be detectable. These predictions are then used to verify the current quality of function. Additional research is going into improving the use of general knowledge such as traffic laws, situational driver behavior to improve predictability. Other top level analysis methods include pedestrian detection.

3.5.3 Measurement Errors

On a physical level measurement errors are shared with other visible light spectrum based systems – fog, rain and dirt reduce the quality of measurement. The measurement principle has been developed to such an extent that the accuracy of a measurement is not significantly affected by environmental changes apart from the changes in visibility. Due to the complex analysis of the data stream it is hard to define the situations for which the analysis will work or fail for sure.

3.5.4 Implications for a Stimulation System

Stimulation at the object level might be easier but due to the large amount of processing it would be hard to ensure that the stimulated objects represent what a real camera system would detect. As mentioned in the introduction a stimulation system will need to be as fast as possible to make sure the scenery is shown correctly for most of the measurement period. Although even then, without synchronization, a single frame delay is possible. As any delay from the simulation and other aspects also add to the total delay such a system would require a validation that its delay does not significantly reduce the performance of the ADAS.

3.6 GPS

The Global Positioning System (GPS) allows the car to identify its position within a digital roadmap. GPS has become a base technology and its use has expanded far beyond its original use in the US military. Consumer electronic navigation systems for automobiles provide position data solely based on GPS data and in some cases a barometer for height measurement. Navigation systems built into cars provide additional accuracy by including data from odometers and other available information within the car such as steering angle and yaw rate. Aside from navigation functions, data from digital maps can also be used for efficient battery management and to improve plausibility checks on object tracking. GPS receivers require three satellite sources in order to determine their position. GPS has an accuracy of 10m but this accuracy can be improved by additional information sources such as the already stated odometry. A system to generate virtual satellite signals for the civil used L1 GPS frequency 1575.42 MHz already exists. Test benches are located indoors which shuts out the original GPS signals and therefore allow the GPS stimulation to be implemented without further obstacles. Due to this circumstance the specifics of GPS need not to be discussed.

4 Stimulation and Simulation for ADAS on HiL and ViL Level

As discussed in previous chapters every sensor system and ADAS comes with a unique set of requirements for testing. Although in HiL and ViL the focus is on testing the integrated unit as a whole the quality of this test relies on the quality of the stimulation system and the quality of the simulation environment.

The stimulation system intercepts at the point between the Device under Test (DUT) and its environment. Ideally it generates the same physical echoes as a real environment would. The second point where stimulation can intercept is at the output of a sensor. The advantages and disadvantages of the two methods for each sensor system were discussed in chapter 3.

In general, the overall validity of the stimulation determines which method is the better choice. Stimulation which aims to generate the same physical echoes as a real environment is usually more effort but requires fewer adaptations between sensor systems. A stimulation which intercepts at the point of object lists emulating the output of a sensor system is generally less effort, but requires more adaptations between different systems and separate validation. For a sensor system which measures in one or two dimensions such as ultrasonic systems and cameras a stimulation through generation of physical signals is achievable with reasonable effort. Stimulation of systems with 3D spatial recognition and large multipath propagation pose a harder problem for stimulation.

The basis of a successful stimulation system is the simulation environment behind it. Whether the sensor is stimulated or the output of the sensor is simulated, the source must be realistic. The stimulation can only be as good as the underlying model of reality. Any simulation uses generalizations which pose possible sources of error. In the case of the CarMaker[1] software used as environment simulation and ultrasonic sensor perception simulation the vertical shapes of objects are dismissed, the differences in reflectivity of surfaces are not considered and irregular surfaces of objects such as trees will not be taken into account. A further improvement of CarMaker or an additional simulation is required, if the stimulation should include these factors. Stimulation of systems with 3D spatial recognition and large multipath propagation pose a harder problem and will also require an additional simulation on the basis of the 3D environment provided by CarMaker. In order to pro-

[1] IPG Automotive GmbH, www.ipg.de

vide real-time testing of ADAS the simulation and stimulation have to fulfill harsh time constraints. Stimulation on the object level as well as on the sensor level can significantly improve the testing procedures for ADAS. Proofing the validity of these methods will be the cornerstone of this improvement.

5 Ultrasonic Stimulation System

Parking assistance systems were the first Advanced Driver Assistance System which entered the mass market. A survey by the German Federation for Motor Trades and Repairs in 2013 showed that a large proportion (49%) of newly licensed cars were equipped with a parking assistance system [14]. Ultrasonic sensors which have already been discussed in chapter 3.1 are the main distance measurement device for this application.

What does "Ultrasonic Stimulation" stand for?

Stimulation is the act of causing a system to exhibit a certain behavior. Ultrasonic waves are the means to achieve this stimulation in the case of parking assistance systems. The goal of ultrasonic stimulation is to cause the device under test (DUT) – the parking assistance system – to behave as if there were objects in its vicinity according to the simulation environment.

The prototype which will be presented here consists of a simulation environment – CarMaker, a signal processing unit (SPU) and an ultrasonic emulation unit (UEU) as shown in Figure 5-1.

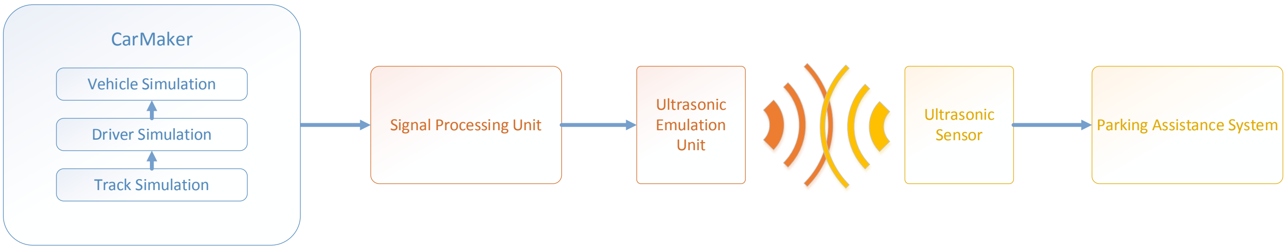


Figure 5-1 Schematic Overview of the Stimulation System

CarMaker provides a virtual environment to perform tests of the assistance system. The focus of this prototype is to establish the link between the simulation environment and the parking assistance system. A feedback from the assistance system to the simulation environment was therefore not required. Based on the 3D scenery the signal processing unit receives the distance between the surface of the closest object and the ultrasonic sensor. The SPU then waits for measurement signals and will generate a stimulation signal according to the given distance. The prototype is designed to elicit echo detection in the parking assistance system. The ultrasonic waves generated by the UEU do not resemble reality. They are shaped and calibrated in such a way that the parking assistance system will certainly detect an echo within a small time error according to the distance. As discussed in chapter 4 a simulation which is capable of generating additional information is required in order to further improve this stimulation system.

The realization of this prototype went through several successive steps. First, the parking assistance system was characterized. Then a signal was generated which could be detected by the parking assistance system. The next step consisted of creating an ultrasonic emulation unit which was capable of signal measurement and conditioning as well as signal generation. A real-time environment (RTE) from dSpace was implemented which could process the output of the signal conditioning unit and activate signal generation after a given time delay. The simulation environment CarMaker was then used as a source for the distance between the ultrasonic sensors and of a virtual object. This distance is transmitted to the RTE where it serves as the base for the calculation of the time delay between echo detection and stimulation signal generation.

5.1 The Parking Assistance System

A parking assistance system from Valeo – Beep&Park (B&P) was chosen as DUT for the stimulation. It is an independent system which can be installed subsequently into any car and consists of four ultrasonic sensors a control unit and a visual display. As no technical documentation was available the relevant characteristics were determined by measurements. Figure 5-2 shows the contents of the parking assistance system as schematic.

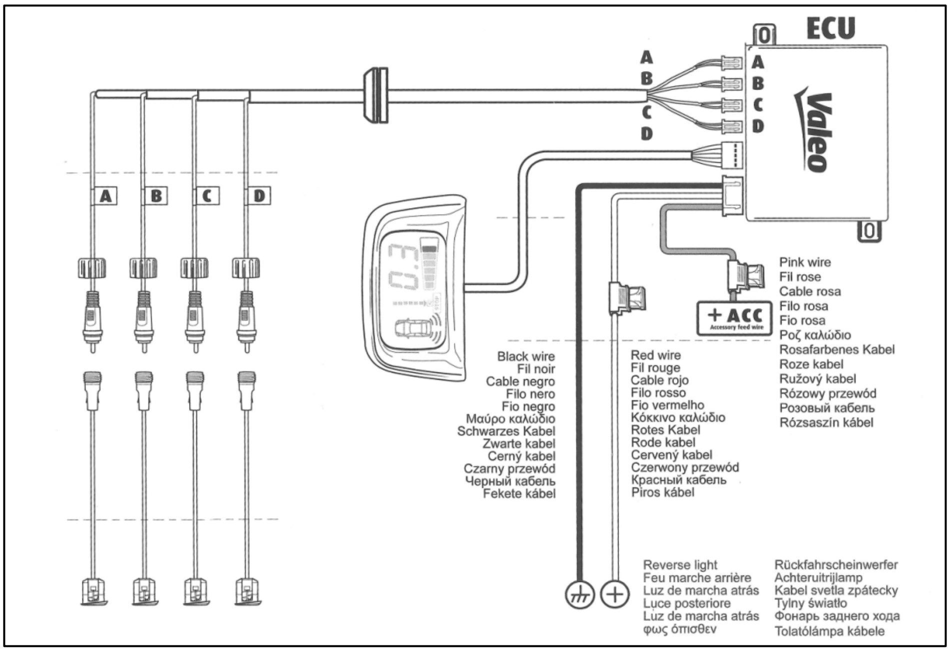


Figure 5-2 Schematic of the Parking Assistance System Valeo B&P n°3

5.1.1 Functionality

The parking assistance requires a supply voltage of +12V which is the usual board net voltage in automobiles. It is activated by changing into reverse gear. This works because the reverse lights are turned on in reverse gear and the parking assistance control unit detects this by measuring the supply voltage of the reverse lights as shown in Figure 5-2. The parking assistance can be activated permanently by connecting the measuring line to +12V which was carried out for this setup. After activation the system determines the distance of objects within range by measuring the time it takes the echo of a generated ultrasonic signal to return to the sensor which generated the signal. In case of B&P there is no cross detection – where one sensor would emit an ultrasonic signal and all sensors would be used to detect it. Therefore the four ultrasonic sensors can be seen as four separate distance measurement units. The accuracy of such a system is limited by several factors as discussed in chapter 2.3.1. The distance of the closest detected object as well as the location of the detecting sensor are then displayed on the display as shown in Figure 5-3 and also expressed through a beep which varies according to the remaining distance from the car.

Figure 5-3 Visual Display of Measured Distances and Parking Recommendation

The system displays the distance and which sensor has measured it between 0.3 and 1.7 meters with a resolution of 0.1 meters. For distances below 0.3 meters a sign which recommends parking is shown.

The parking assistance system also has a fault detection system which monitors whether a sensor is functioning as expected or not. If a faulty sensor is detected this is displayed and input from that sensor is then ignored for a given period of time and until the behavior returns to what is expected. Such a fault detection occurs e.g. when the stimulation system fails to synchronize with the measurement signal.

5.1.2 Measurement Process

A measurement cycle starts with signal generation which will be discussed in 5.1.3. The generated signal with a frequency of 40 kHz radiates outward and is reflected by any surface. This reflection will then stimulate the ultrasonic sensor to generate an alternating voltage. This voltage is amplified and filtered as part of signal conditioning. The distance to the closest object is determined in the calculation unit by the time it took the echo to return to the sensor. The hardware of this cycle is shown in Figure 5-4.

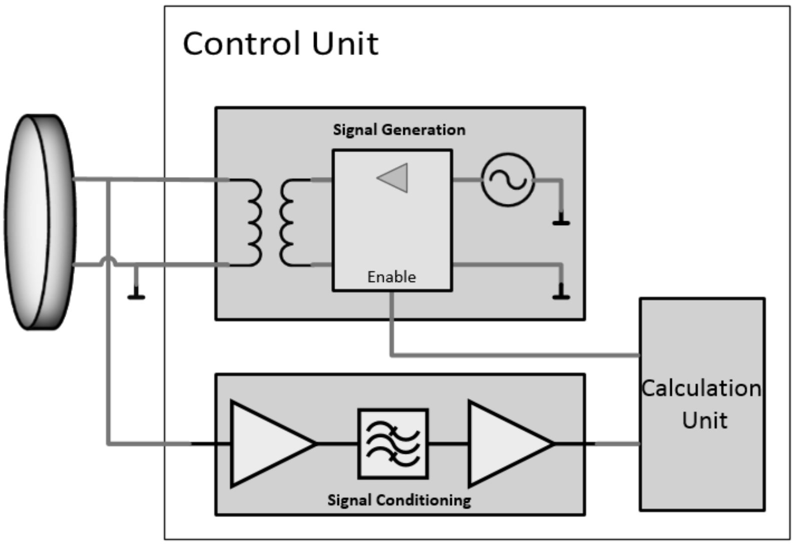


Figure 5-4 Schematic view of the Ultrasonic Measurement Units

There are two major ways to arrange these signal processing steps. In analog ultrasonic sensors only the transformation of electrical energy to ultrasonic sound and backwards is located in the sensor and the rest is placed in the control unit. In digital sensors these signal processing steps are within each sensor unit. In this case the control unit communicates with the sensor through a communication protocol, e.g. Local Interconnect Network (LIN), and gives commands to generate a signal after which it listens until the sensor transmits a detection signal. Valeo Beep&Park uses the former version.

5.1.3 Signal Generation

Automotive ultrasonic sensors have a durable metallic membrane due to the long life cycle of cars. This durability comes at the cost of decreased flexibility of the membrane. Typical ultrasonic sensors require 120V_{PP} at 40–50 kHz with rectangular waveform to generate ultrasonic signals. B&P sends at 140V_{PP} and 40 kHz as can be seen in Figure 5-5. The sensor is stimulated for 500µs and it takes additional 250µs for the oscillation to attenuate. The sudden change in phase shift at 500µs is taken as a sign for a switch from sink to source by the transformer inductance which marks the start of attenuation.

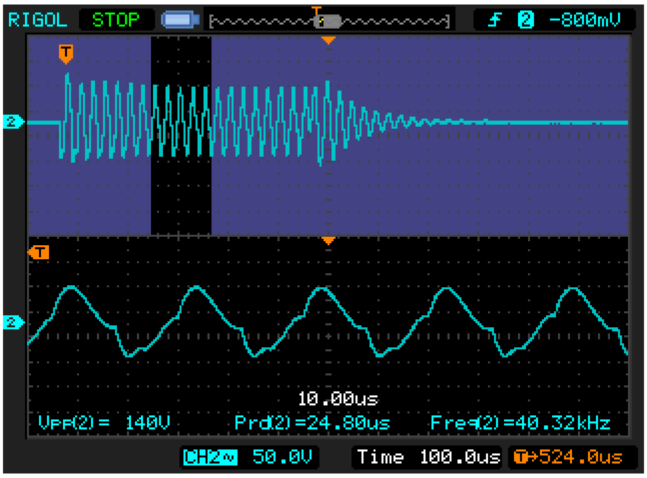


Figure 5-5 Signal Generation

The sensing pattern consists of two distance measurements separated by 180ms followed by a measurement after 100ms. When an object is detected two additional measurements separated by 28ms are added after the 100ms measurement as can be seen on the right of Figure 5-6. These additional measurements are used to calculate the velocity by determining the change in distance through numerical differentiation. All measurements were made with a RIGOL DS1002E digital oscilloscope.

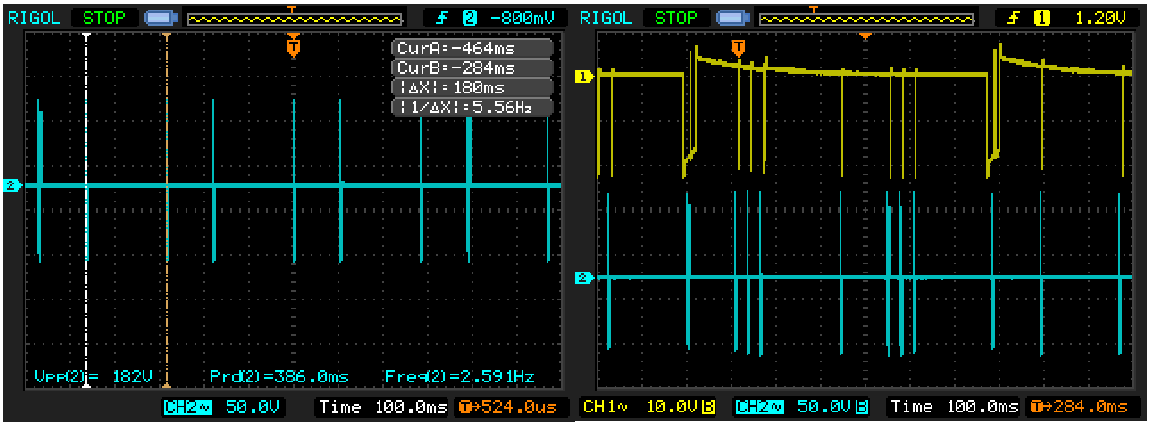


Figure 5-6 Detection Pattern when no Echo is Detected (left) and when an Echo is Detected (right)

The sensitivity of the system is hard to determine directly as the measuring channel of the oscilloscope is exposed to the 140 V_{PP} sending signal which causes an oscillation that lasts longer than the measurement period. Figure 5-7 shows the impact of a stimulation signal generated with 25 V_{PP} for a distance of 1.7m. The larger timescale in the upper half of the figure shows the attenuating oscillation in the measurement channel. The lower half shows the superimposed alternating voltage caused by the stimulation signal, roughly $20mV_{PP}$.

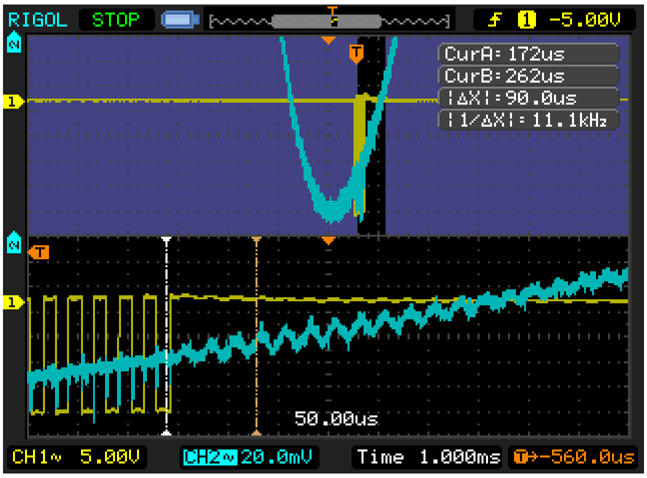


Figure 5-7 Detection Sensitivity, Stimulation Signal: Yellow

A stimulation voltage of 3 V_{PP} could still be detected which equals an estimated sound pressure of 4.2 Pascal and a resulting voltage of $3.4mV_{RMS}$ as calculated in Table 4 (No. 3).

5.1.4 Ultrasonic Sensor Characterization

Both the sensors of the parking assistance system as well as the sensors of the ultrasonic emulation unit - the KPUS-40FD-14TR-669 (KPUS) were characterized. The parking assistance system and the Black Star Jupiter 2000 0.2 Hz–2 MHz function generator set to rectangular signal form were used to drive the transmitting ultrasonic sensor. Measurements were made with the RIGOL DS1002E digital oscilloscope. Figure 5-8 shows the quantities which were measured or calculated: source voltage U_S, sound pressure level (SPL), sound pressure p, sensitivity and the received voltage U_R. Figure 5-8 also shows how transmitting and receiving sensors were arranged in measurements 1–3.

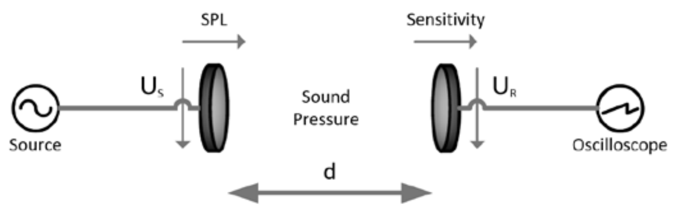


Figure 5-8 Measurement Setup 1, 2 & 3

In measurement setup 1 the KPUS-40FD-14TR-669 (KPUS) ultrasonic sensor was measured. According to its datasheet the KPUS sensor has a sensitivity S of $-87dB$ at $30cm$ and

40 kHz with $0dB = 10V/Pa$ and a sound pressure level (SPL) of $103dB$ at $10V_{RMS}$ with $0dB = 0.02mPa$. The sensitivity describes how much voltage is generated by a Pascal of sound pressure p [$\frac{kg}{m\,s^2}$] in decibel [19]. The decibels are calculated with respect to a given reference here $s_0 = \frac{10V}{Pa}$.

$$S = 20 * log_{10}\left(\frac{\frac{U_R(V)}{p(Pa)}}{s_0}\right) \quad (5\text{-}1)$$

The sound pressure level [19] describes how much sound pressure a sensor generates from a given voltage in decibels with respect to a reference sound pressure p_0 here $p_0 = 0.02mPa$. The SPL usually describes the amount of sound pressure which can be measured at 30cm distance from the source.

$$SPL = 20 * log_{10}\left(\frac{p * \frac{10V_{RMS}}{U}}{p_0}\right) \quad (5\text{-}2)$$

Table 1 shows the measurements and calculations which were made.

Set		Measured		Calculated					
No.	d	U_S	U_R	U_S	U_R	p from U_S	S	p from U_R	SPL
	cm	V_{PP}	V_{PP}	V_{RMS}	V_{RMS}	Pa	dB	Pa	dB
1	30,0	24,0	1,20E-02	12,0	4,24E-03	3,39	-78,05	9,50	111,95
2	3,0	24,0	9,68E-02	12,0	3,42E-02	33,90	-79,92	76,62	110,08
3	1,0	24,0	3,66E-01	12,0	1,29E-01	101,70	-77,91	289,69	112,09

Table 1 Transmitter KPUS, Receiver KPUS Measurement Setup 1

The effective voltage of a rectangular signal is its amplitude, so

$$U_S(V_{RMS}) = \frac{V_{PP}}{2} = \frac{24V}{2} = 12V\ (Nr.1) \quad (5\text{-}3)$$

The effective voltage of a sine is the square root of its amplitude so

$$U_R(V_{RMS}) = \frac{V_{PP}}{2 * \sqrt{2}} = \frac{12mV}{2 * \sqrt{2}} = 4.24mV\ (Nr.1) \quad (5\text{-}4)$$

The KPUS sensor, according to its datasheet, has a sound pressure level (SPL) of $103dB$ at $10V_{RMS}$ with 0dB being $20\mu Pa$ in 30cm distance. Using this datasheet sound pressure level (SPL_D) the sound pressure acting upon the receiver is calculated with:

$$p = p_0 * 10^{\frac{SPL}{20}} * \frac{U_S}{10V_{RMS}} = 20\mu * 10^{\frac{103}{20}} * \frac{12}{10} = 3.390\,Pa \;\; (Nr.1) \qquad (5\text{-}5)$$

Sound pressure falls approximately by $\frac{1}{r}$ inversely proportional to the distance from a point source [19] [21], this relation is called the distance law for sound pressure:

$$p \propto \frac{1}{r} \qquad (5\text{-}6)$$

With r being the distance from the source. This relation is used to estimate the sound pressure at distances shorter than 30cm.

$$p = p_0 * 10^{\frac{SPL_D}{20}} * \frac{U_S}{10V_{RMS}} * \frac{\frac{1}{d}}{\frac{1}{30}} = 20\mu * 10^{\frac{103}{20}} * \frac{12}{10} * \frac{\frac{1}{3}}{\frac{1}{30}} = 33.90\,Pa\,(Nr.2) \qquad (5\text{-}7)$$

With the sound pressure and the measured voltage U_R the sensitivity can be calculated. The sensitivity is based on $10V/Pa$.

$$S = 20 * log_{10}\left(\frac{\frac{U_R(V)}{p(Pa)}}{s_0}\right) = 20 * log_{10}\left(\frac{\frac{4.24mV}{3.390Pa}}{\frac{10V}{Pa}}\right) = -78.5dB\,(Nr.1) \qquad (5\text{-}8)$$

Working backwards from the measured U_R with the sensitivity from the datasheet the sound pressure which acts upon the receiving sensor is calculated as:

$$p = \frac{U_R}{s_0 * 10^{\frac{S_D}{20}}} = \frac{4.24mV}{\frac{10V}{Pa} * 10^{-\frac{87}{20}}} = 9.5\,Pa\,(Nr.1) \qquad (5\text{-}9)$$

From this sound pressure the sound pressure level of the sensor is calculated with a reference voltage U_S of $10V_{RMS}$.

$$SPL = 20 * log_{10}\left(\frac{p * \frac{10V_{RMS}}{U_S}}{p_0}\right) = 20 * log_{10}\left(\frac{9.5Pa * \frac{10V}{12V}}{20\mu Pa}\right) = 111.95dB\ (Nr.1) \quad (5\text{-}10)$$

In order to estimate the SPL from measurements where the sending and receiving sensor were less than 30 cm apart the relation of sound to its source is used again.

$$SPL = 20\,log_{10}\frac{p * \frac{10V_{RMS}}{U_S} * \frac{\frac{1}{30}}{\frac{1}{d}}}{p_0} = 20\,log_{10}\frac{76.2Pa * \frac{10V}{12V} * \frac{\frac{1}{30}}{\frac{1}{3}}}{20\mu P} = 110.08dB(Nr.2)\,(5\text{-}11)$$

Calculating the sensitivity and the SPL in both directions results in values which are significantly better than the datasheet guarantees. This suggests that either the sensor is better at creating ultrasound, receiving ultrasound or the measurement setup allowed for reflections which improved transmission.

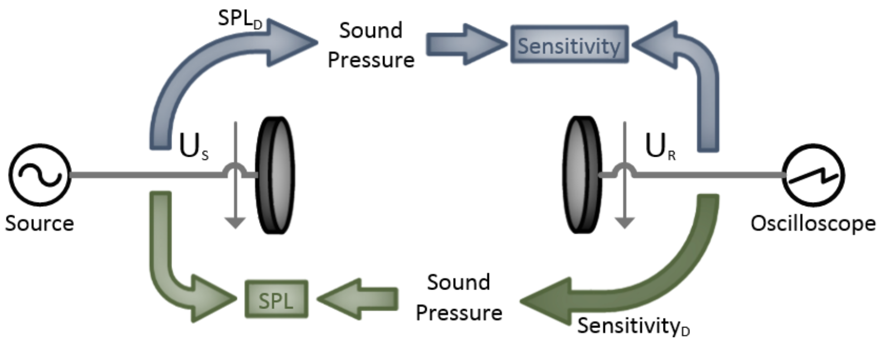


Figure 5-9 Two Directions of calculating Sensitivity and SPL

In order to improve the accuracy of the Valeo B&P sensor characterization SPL and sensitivity of the KPUS needs to be determined as accurate as possible. As shown in Figure 5-9 the sound pressure is not measured directly and therefore SPL and sensitivity can only be approximated. Neglecting any errors by sound propagation the SPL and sensitivity required to fit the measurement in Table 1 (No. 1) are calculated. For this calculation a relation between the source and received voltage needs to be established. This approximation is done by calculating SPL and sensitivity from the relation between sent and received voltage which can be obtained through equating Equation (5-5) and Equation (5-9):

$$p = p_0 * 10^{\frac{SPL}{20}} * \frac{U_S}{10V_{RMS}} = \frac{U_R}{s_0 * 10^{\frac{S}{20}}} \quad (5\text{-}12)$$

By rearranging Equation *(5-12)* U_R is calculated with:

$$U_R = p_0 * s_0 * \frac{U_S}{10V_{RMS}} * 10^{\frac{SPL}{20}} * 10^{\frac{S}{20}} \qquad (5\text{-}13)$$

The sensitivity reference $s_0 = \frac{10V}{Pa}$ as used in this document cancels with the $10V_{RMS}$ and the exponentials can be pulled together yielding:

$$U_R = \frac{U_S}{10V_{RMS}} * 10^{\frac{SPL+S}{20}} \qquad (5\text{-}14)$$

Substituting $SPL + S$ for T and solving for T yields:

$$T = 20 * log_{10}\left(\frac{U_R}{p_0 * U_S}\right) = 20 * log_{10}\left(\frac{4{,}24mV}{20\mu P * 12V}\right) = 24{,}9dB \qquad (5\text{-}15)$$

Calculating T_D from the datasheet values leads to:

$$T_D = SPL_D + S_D = 103dB + (-87dB) = 16dB \qquad (5\text{-}16)$$

As the piezoelectric effect and the reciprocal piezoelectric effect are related it is assumed that the difference between measured T and datasheet T_D is distributed equally for the calculation of the approximated SPL and S:

$$\Delta T = T - T_D = 8{,}9dB \cong 9dB \qquad (5\text{-}17)$$

$$SPL = SPL_d + \frac{\Delta T}{2} = 103dB + 4{,}5dB = 107{,}5dB \qquad (5\text{-}18)$$

$$S = S_d + \frac{\Delta T}{2} = -87dB + 4{,}5dB = -82{,}5dB \qquad (5\text{-}19)$$

For further calculations the values of Equation (5-18) and (5-19) are used.
Measurements from setup 2 and 3 were performed to determine SPL and sensitivity of the B&P ultrasonic sensors. Table 2 and Table 3 show the measurements and calculations.

Set		Measured		Calculated			
No.	d	U_S	U_R	U_S	U_R	p from U_S	S
	cm	V_{PP}	V_{PP}	V_{RMS}	V_{RMS}	Pa	dB
1	30,0	24,0	5,00E-02	12,0	1,77E-02	5,69	-70,16
2	3,0	24,0	2,28E-01	12,0	8,06E-02	56,91	-76,98
3	1,0	24,0	6,56E-01	12,0	2,32E-01	170,74	-77,34

Table 2 Transmitter KPUS, Receiver Valeo B&P Measurement Setup 2

Set		Measured		Calculated		
No.	d	U_S	U_R	U_R	p from U_R	SPL
	cm	V_{RMS}	V_{PP}	V_{RMS}	Pa	dB
1	30,0	42,7	5,40E-02	1,91E-02	25,46	109,49
2	3,0	42,7	3,51E-01	1,24E-01	165,49	105,75
3	1,0	42,7	7,12E-01	2,52E-01	335,69	102,35

Table 3 Transmitter Valeo B&P, Receiver KPUS Measurement Setup 3

The same calculations as for Table 1 were made. According to these measurements the B&P sensors have a SPL of $109{,}49dB$ and a sensitivity of $-70{,}19dB$. While the measurements at closer distances were useful to see how high the sound pressure is at distances similar to the prototype setup they are too close to be useful for the calculation of the SPL and sensitivity as the assumption from Equation (5-6) is an approximation which only accurately applies for point sources and can therefore not be used to improve accuracy of SPL and sensitivity.

Measurement 4 and 5 were carried out with the sensors arranged as in the prototype setup shown in Figure 5-11 and Figure 5-11. A separate sensor is used for stimulation and detection. For both signal paths the received voltage was determined. Calculations for SPL and sensitivity were carried out, but only apply to this scenario due their alignment being at a right angle and due to the high amount of reflections by the shell of sound absorbers which are indicated grey.

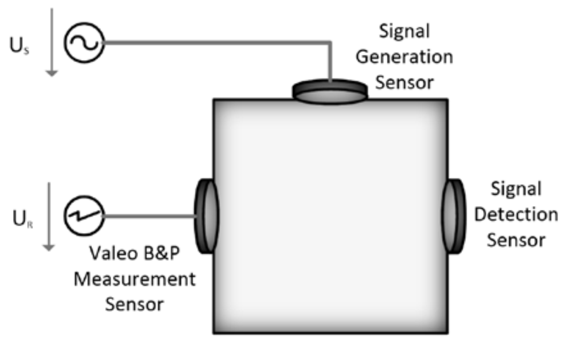


Figure 5-11 Measurement Setup 4

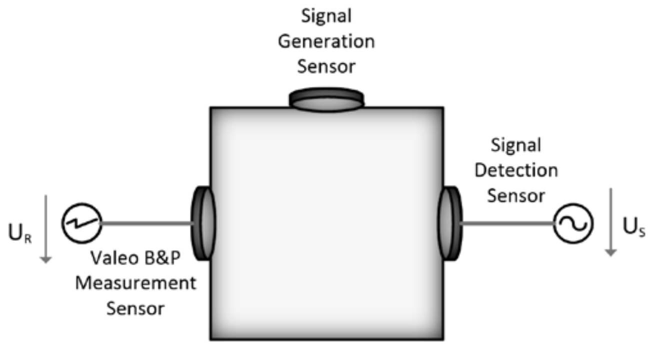


Figure 5-10 Measurement Setup 5

Set		Measured		Calculated					
No.	d	U_S	U_R	U_S	U_R	p from U_S	S	p from U_R	SPL
	cm	V_{PP}	V_{PP}	V_{RMS}	V_{RMS}	P	dB	Pa	dB
1	3,0	24,0	6,00E-02	12,0	2,12E-02	56,91	-88,57	11,93	93,93
2	3,0	10,0	2,40E-02	5,0	8,49E-03	23,71	-88,93	4,77	93,57
3	3,0	3,0	9,60E-03	1,5	3,39E-03	7,11	-86,43	1,91	96,07

Table 4 Transmitter KPUS, Receiver Valeo B&P Measurement Setup 4

The sound pressure from U_R is based on the determined sensitivity of $-70{,}19dB$.

Set		Measured		Calculated	
No.	d	U_S	U_R	U_R	p from U_R
	cm	V_{RMS}	V_{PP}	V_{RMS}	Pa
1	3,0	42,7	2,00E-01	7,07E-02	94,29

Table 5 Transmitter Valeo B&P, Receiver KPUS Measurement Setup 5

U_R of measurement 5 is used as the basis for the calculation of the signal conditioning circuit.

5.1.5 Hardware Requirements

Based on the measurements made in chapter 5.1.4 requirements for the simulation sensor and hardware are calculated. This includes the minimum and maximum sound pressure as well as the required amplification for the signal conditioning unit.

The maximum distance measured is 1.7 meters and the minimum distance is 0.3meters. Assuming that no power is lost by reflection the sound pressure at a given distance can be calculated by $\frac{1}{r}$. With a measured $42{,}7V_{RMS}$ source voltage and a SPL of $109{,}49dB$ the sound wave sent out by Valeo B&P after travelling 10cm/3,4m extorts 76,4/2,25Pascal onto the measuring sensor according to Equation (5-11). Further calculation by rearranging Equation (5-9) yields that this would equal detection voltages of 236mV/6,9mV. Table 4 shows that these requirements could be met by the stimulation. For the design of a signal generation hardware rearranging Equation (5-11) leads to the required source voltages $16{,}1V/0{,}47V$:

$$U_S = \frac{p * 10V_{RMS} * \frac{\frac{1}{30}}{\frac{1}{d}}}{p_0 * 10^{\frac{SPL}{20}}} = \frac{76{,}4 * 10V_{RMS} * \frac{\frac{1}{30}}{\frac{1}{3}}}{20\mu Pa * 10^{\frac{107{,}5}{20}}} = 16{,}1V \qquad (5\text{-}20)$$

As ultrasonic sensors with up to 50 kHz resonance frequency are used, a hardware signal generation would have to be capable of creating 40–50 kHz.

5.2 Ultrasonic Emulation Unit

The UEU is designed as interface between Valeo Beep&Park and the signal processing unit. This requires signal generation and signal conditioning. The signal generation must be capable of providing a rectangular frequency of 40–50 kHz and voltages $16.1V - 0.47V$ as calculated in chapter 5.1.5. It should respond as fast as possible to activation and enable the ultrasonic sensor to attenuate as fast as possible after signal generation. The signal conditioning must be capable of amplifying and filtering the received $70{,}2mV_{RMS}/200mV_{PP}$ up to 10V for the A/D of the signal processing unit. Figure 5-12 shows how Valeo B&P, signal generation, signal conditioning and the signal processing unit are connected.

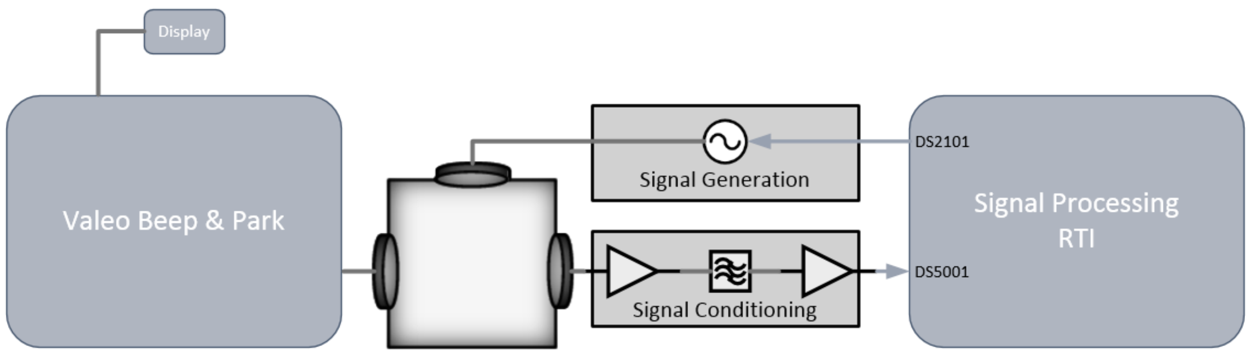


Figure 5-12 Ultrasonic Stimulation System

5.2.1 Signal Generation

The stimulation signal is generated with the Jupiter 2000 frequency generator. Voltage and frequency can be set manually. The activation is realized by exploiting the frequency sweep channel. Applying a voltage of 0V enables the generation frequency at 40 kHz as shown in Figure 5-13 (left). Figure 5-13 (right) shows the shape of the generated frequency when turned “off” by applying +10V to the sweep channel. The signal resembles a PWM with a duty cycle of 91.4% and a frequency of 4.31 Hz. The minimum time between two edges is 20ms which is short enough to influence the detection tree in one measurement cycle. The signal detection of the signal processing unit is adjusted to limit this influence (5.3.1).

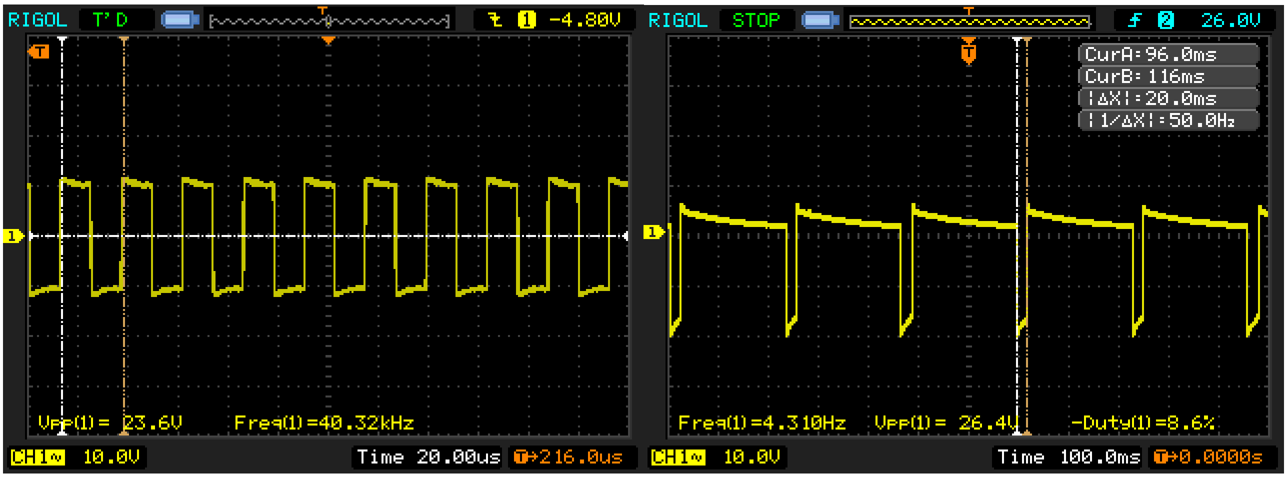


Figure 5-13 Signal Generation before and after applying +10V to the Sweep Channel

5.2.2 Signal Conditioning

The signal conditioning consists of a voltage follower and an active band pass both realized with a general purpose operational amplifier (OpAmp). The voltage follower is used to ensure that the source is not influenced by the signal conditioning. The OpAmp was chosen so that its characteristics are negligible to the performance of the circuit.

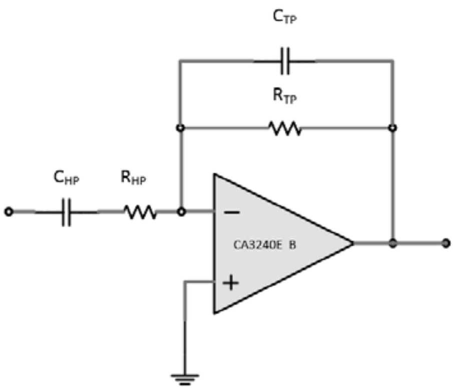


Figure 5-14 Schematic of the active Band Pass

The structure of the active band pass is shown in Figure 5-14. The frequency to be amplified is 40 kHz. In order to incorporate the tolerance of capacitors the cutoff frequencies were chosen further apart with $c_{HP} = 20\ kHz$ for the high pass and $c_{TP} = 60kHz$ for the low pass. The piezoelectric crystal of the receiving ultrasonic sensor generates a voltage of about $200mV_{PP}$. Using the whole available voltage range of 12V leads to an amplification of $V = \frac{10V}{200mV} = 60$. The OpAmp used does not have a rail-to-rail output stage and therefore requires a voltage difference between source V+/V- and output voltage of 2-2.5V for V+ and

0.8-0.3V for V-. Therefore, a gain less than 60 is sufficient and in addition the A/D of the signal processing unit only measures in a 10V range anyway. The values were chosen as follows:

$$R_{TP} = 39k\Omega, R_{HP} = 820\Omega, R_1 = R_2 = 8{,}2k\Omega$$

$$C_{TP} = 68pF, C_{HP} = 10nF, C_1 = 68\mu F$$

This leads to the following cutoff frequencies and gain:

$$f_{c_{TP}} = \frac{1}{2 * \pi * R_{TP} * C_{TP}} = \frac{1}{2 * \pi * 39k\Omega * 68pF} = 60.01kHz \qquad (5\text{-}21)$$

$$f_{c_{HP}} = \frac{1}{2 * \pi * R_{HP} * C_{HP}} = \frac{1}{2 * \pi * 820 * 10nF} = 19.41kHz \qquad (5\text{-}22)$$

$$V = -\frac{R_{TP}}{R_{HP}} = -\frac{39k\Omega}{820\Omega} = -47.6 \qquad (5\text{-}23)$$

The whole signal conditioning stage is shown in Figure 5-15. C_1 serves as local voltage stabilization; R_1 and R_2 are used to set the DC voltage of the ultrasonic sensor to +5V to allow symmetric amplification as no negative voltage was available.

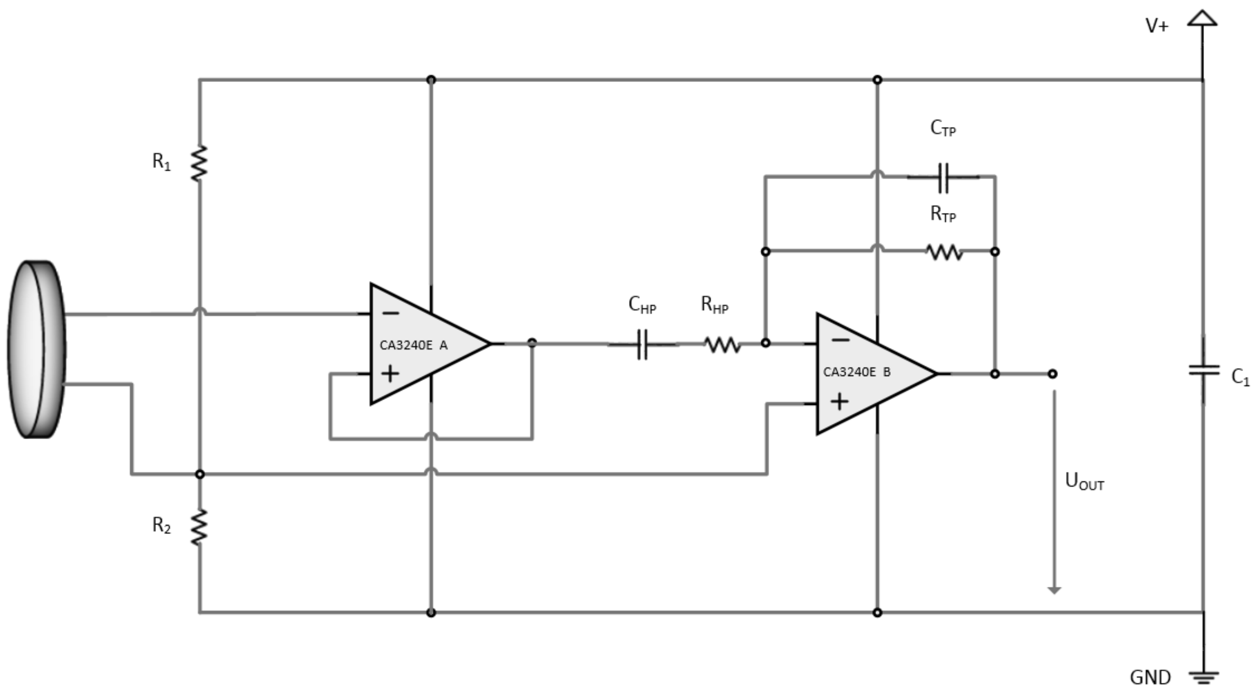


Figure 5-15 Signal Conditioning Stage

5.3 Signal Processing Unit

As signal processing unit the DS1005 real-time environment (RTE) from dSpace was used. This system consists of the DS5001 Digital A/D Card for signal detection and the DS2101 D/A Card for signal generation activation. The code for the RTE is generated based on a Simulink model via the dSpace real time interface (RTI) which is loaded to the RTE via ControlDesk. ControlDesk also allows monitoring and directly changing any variable in the RTE. Figure 5-16 shows the whole system.

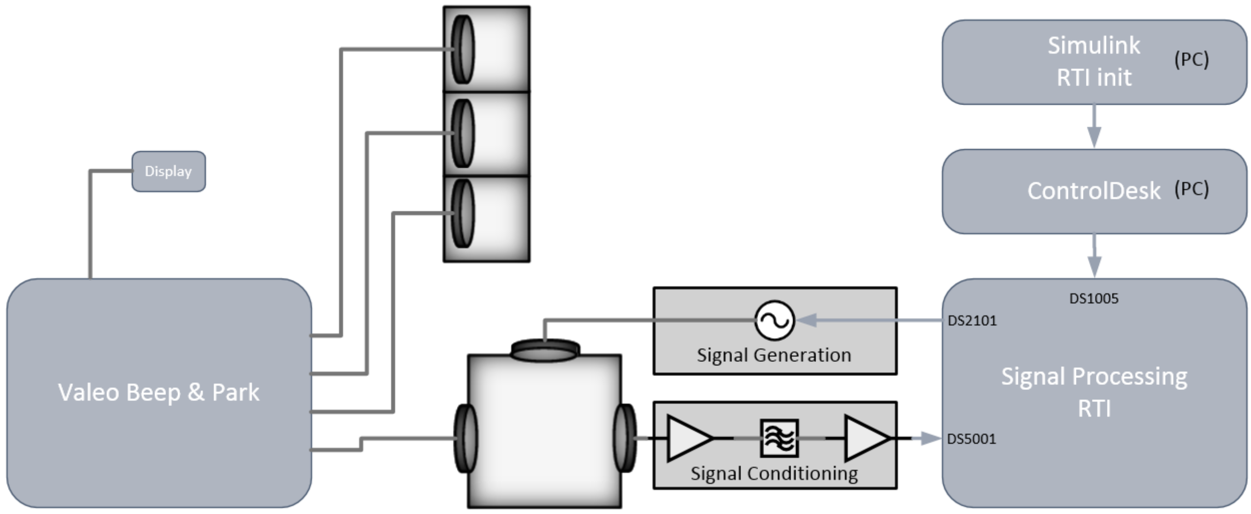


Figure 5-16 Ultrasonic Stimulation System

5.3.1 Detection

Channel 3 of the DS5001 Digital Signal A/D Card was used for signal detection. Its trigger level can be set between +/- 10V and is able to detect rising and or falling edges across a given trigger threshold. In this case the trigger level is set to 1.4V this value was chosen high enough to avoid noise triggers but also as low as possible to detect the incoming signal as soon as possible as can be seen in Figure 5-19. The DS5001 records up to 512 edges with a timescale of 25ns between two readouts. With the period to be measured being $T = \frac{1}{f} = \frac{1}{40kHz} = 25\mu s$ which translates into an edge every 12.5µs this is easily achieved. The DS2001 A/D Card which was also available could not be used as the minimum execution time of the RTE was 15µs. According to the Shannon theorem an execution time below 12.5µs would have been required. The DS5001 is set to issue an interrupt after detecting four edges. As the signal generation in its “off” state will cause at most two edges it is therefore ensured that Valeo B&P is sending out a measurement pulse when the interrupt is triggered.

5.3.2 Signal Generation Activation

Signal generation is activated by setting channel 2 of the DS2101 D/A Card to 0. Setting the output to 1 will cause the D/A unit to produce a voltage of 10V.

5.3.3 Calculation / Real-Time Environment

The processing of information happens within the real-time environment. The tasks of the RTE are generated from a Simulink model which is shown in Figure 5-17.

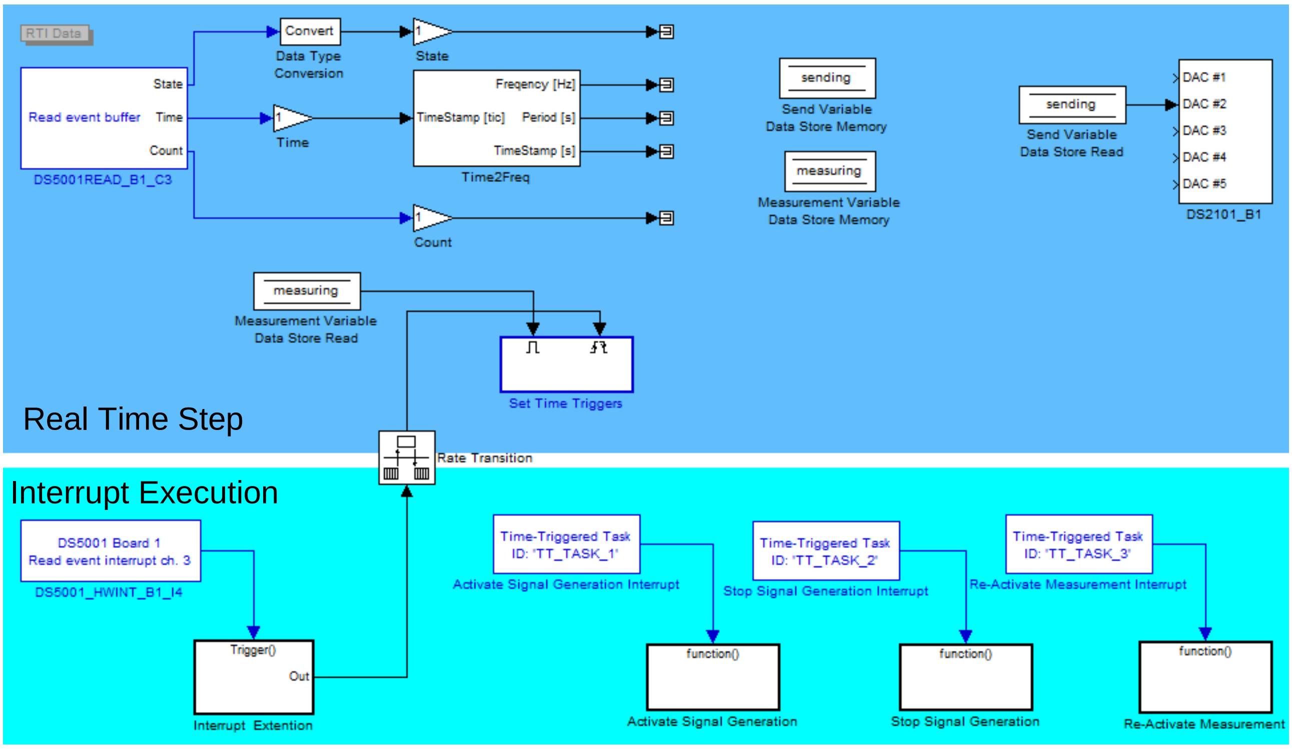
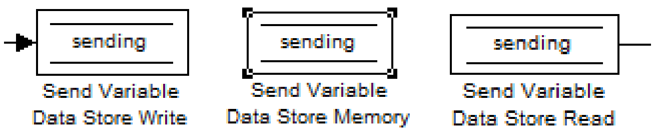


Figure 5-17 Simulink Calculation Configuration

dSpace provides Simulink blocks to integrate their boards easily, but with limited functionality. To understand how the signal processing works a distinction between real time step calculations and interrupts must be drawn. All regular calculations are carried out repeatedly during real-time steps. In the case of this system a real-time step (RTS) was chosen with 70µs.15µs was the shortest possible duration, but in order to avoid processing time jams 70µs were chosen. At the beginning of this RTS the read event buffer of DS5001 and any data which was written into the rate transition block is passed on now. With this new data calculations are carried out. At the end of each real-time step the data store read blocks are updated and the new values are written to the outputs, in this case the DS2101_B1. Interrupts are executed immediately and trigger a subsystem which is then carried out immediately. Ideally, the signal generation would be activated exactly after the desired time delay after signal detection. Unfortunately, a function triggered by an interrupt cannot set new time triggers and also the data store read blocks are only carried out during a time step which adds additional time delay after sending is set or deactivated. This leads to variations in the actual time delay between detection and activation which are examined in chapter 5.3.3.



Data store memory blocks can be accessed from multiple sources by data store read and data store write blocks. The variables “sending” and “measuring” are used to realize the time dependent behavior of the Stimulation.

Sending

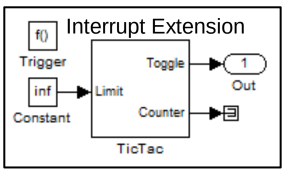
Sending is the variable controlling the voltage output of the DS2101 and is either set to 1 which disables frequency stimulation at the end of the next RTS or set to 0 in which case 40 kHz are generated by the Jupiter 2000.

Measuring

Measuring controls whether or not a stimulation cycle can be started. As soon as a stimulation cycle is started “measuring” is set to 0 disabling the set time triggers block. It is enabled again after the stimulation signal has attenuated.

Description of One Stimulation Cycle:

The parking assistance sends out a measuring signal. This signal generates an alternating voltage in the detection tree which is conditioned and the edges are recorded. Upon detecting four edges the hardware interrupt is activated. This triggers the interrupt extension



which toggles its output each time it is called. The rate transition will pass this edge along in the next time step and trigger the set time triggers routine if “measuring” is set to 1. This routine will disable measurement $Write \rightarrow "Measuring = 0"$, and set three time triggered interrupts according to the desired object distance as shown in Figure 5-18.

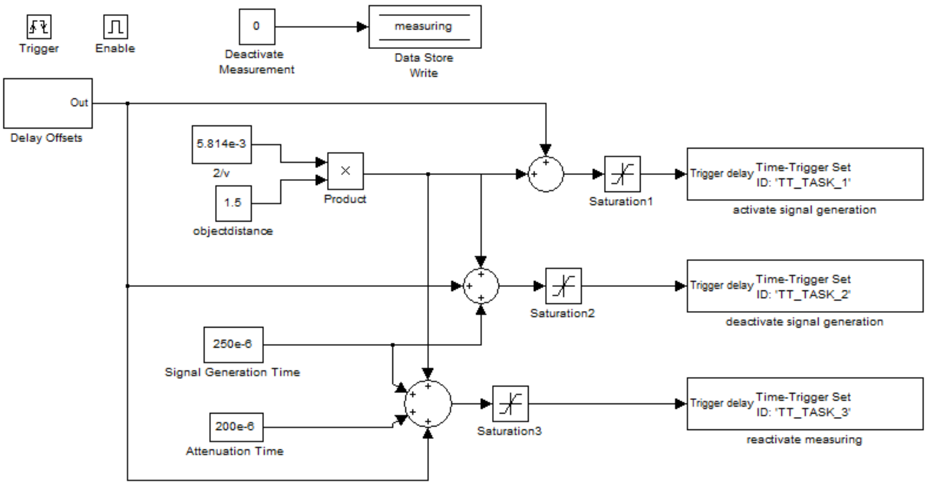


Figure 5-18 Set Time Triggers

The first will be activated after $t = \frac{v}{2} * objectdistance - t_d$ with s being the desired object distance and enable the signal generation $Write \rightarrow "Sending\ = 0"$ The second starts 250µs after the first and disables signal generation $Write \rightarrow "Sending\ = 1"$. The third will reactivate measurement $Write \rightarrow "Measuring\ = 1"$ an additional 200µs later - after the echo of the signal generation has attenuated. The subsystem Delay Offsets (Figure 5-22) provides a total delay offset $t_d = 464\mu s$ based on the results of 5.3.4. The saturation blocks are put in to insure no negative times are set for the interrupts as would result from any distance below $s = \frac{v}{2} * t_d = \frac{344}{2} * 464\mu s = 7{,}98cm$.

5.3.4 Timing and Resolution Analysis

The parking assistance system displays at a resolution of 0.1 m. To achieve this accuracy a minimum time resolution of $t = \frac{(2*s)}{V} = \frac{0.2}{344} = 580\mu s$ is required. It is likely that the system is above this minimum. As a rule of thumb the ultrasonic stimulation should achieve a time resolution of 58µs to ensure correct function. Newer parking assistance systems might require higher time resolution accuracy. The delay time is subject to two types of error: systematic error (time delay offset) and stochastic error (time delay variation). The system built upon this ultrasonic stimulation prototype should have a calibration phase in which the time delay is adjusted until the distance measurement by the parking assistance system equals the desired object distance. Systematic time offsets from software execution and hardware signal propagation times could be eliminated by such a calibration.

Systematic Time Delay Offset

As no direct feedback between the output of the parking assistance system and the ultrasonic stimulation unit has been established, the major contributors to time offset have been determined directly. Hardware time delays are caused from the distance between the Valeo B&P sensor and detection sensor, signal conditioning and signal generation. The time offset between signal generation by Valeo B&P and the output of the signal conditioning is 188µs as shown in Figure 5-19. The time until the signal conditioning output rises above the trigger level is measured here.

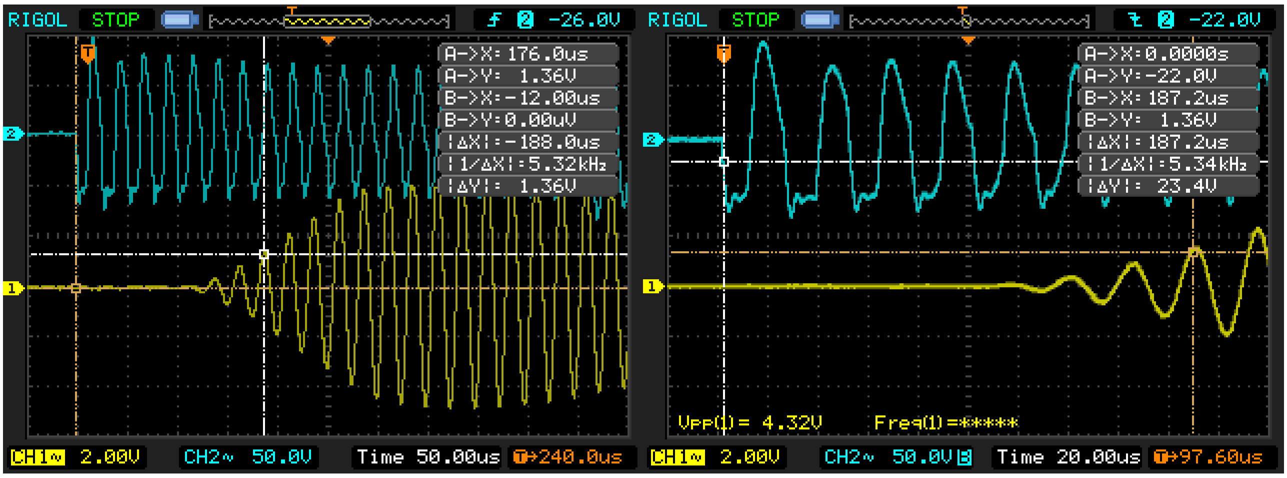


Figure 5-19 Signal Detection Delay

The time delay between signal generation activation and reception by the parking assistance system is between 206 and 218µs as shown in Figure 5-20.The signal in blue was digitally filtered by a band pass (15 kHz–60 kHz) in order to eliminate noise.

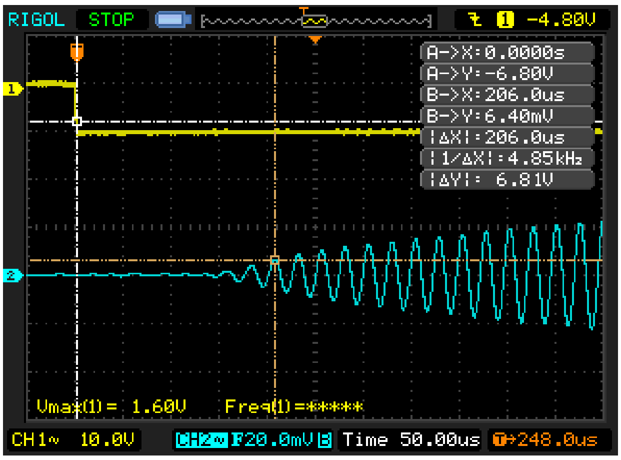


Figure 5-20 Signal Generation Delay

This variance is caused by the Jupiter 2000 frequency generator which requires between 12.8µs and 24.8µs to respond to the change of voltage at its frequency sweep channel as shown in Figure 5-21.

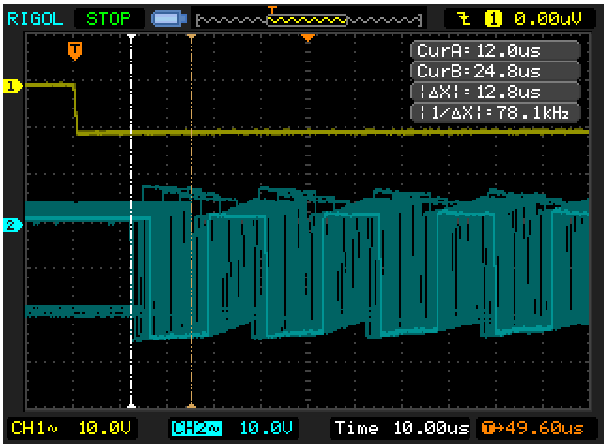


Figure 5-21 Signal Generation Activation Delay

Further offset is introduced by the requirement of four edges for interrupt activation. This causes an additional delay of 50µs. Figure 5-22 shows the systematic time delay correction subsystem.

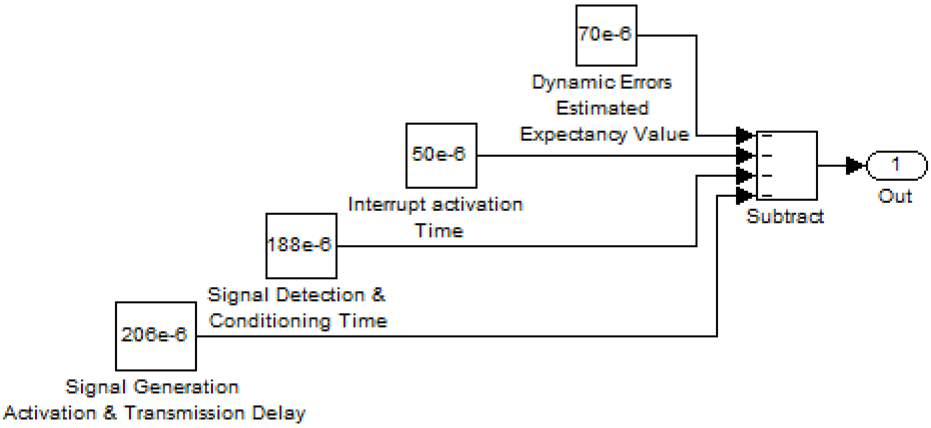


Figure 5-22 Systematic Time Delay Correction

A further analysis of delay variation would allow calculating the expectancy value of time delay variance which could then also be added to the static time offsets to decrease static time delay offset to a minimum. As the next version of this stimulation will tackle largely removing time delay variation this was not carried out, but according to the results provided in Figure 5-25 delay variation expectation value is estimated with 70µs.

Time Delay Variance

The second type of time delay error is time delay variance. These measurements were made with a distance setting of 1.5m. This prototype has a time delay variance between 119.5µs and 202µs depending on the semi static time delay. The time delay as measured in Figure 5-23 exhibits a time delay variance of 124µs which translates to a distance error of:

$$\Delta s = \frac{\Delta t * v}{2} = \frac{124\mu s * 344\frac{m}{s}}{2} = 2{,}13cm \qquad (5\text{-}24)$$

Fortunately the parking assistance system averages its measurements, which further reduces the impact of this variation.

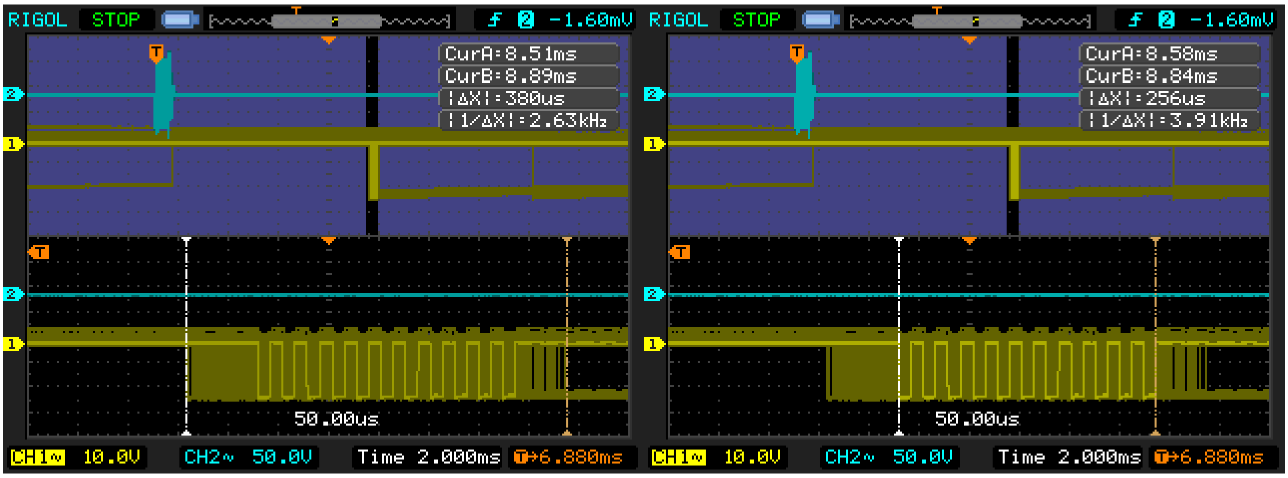


Figure 5-23 Time Delay Variance

This variance is caused by multiple sources such as the “off” state of the signal generation and the interplay between real time steps and interrupts as mentioned in chapter 5.3.3. The signal generation in its “off” state causes up to two detected edges thereby shortening the response of the hardware interrupt by up to 25µs; in Figure 5-23 only a single edge occurred causing 12.5µs variance. The rate transition from the interrupt extension to the “Set Time Triggers” block leads to a time variation as the latter is only executed every RTS. If the interrupt is triggered close to the next time step the additional delay is small, and if it is triggered right after a time step the delay lasts up to the sample time of the RTE in this case 70µs. The setting of the D/A outputs also happens only at the end of a real-time step. Here the maximum delay again, is the sample time of the RTE being 70µs for signal generation activation as well as for deactivation.

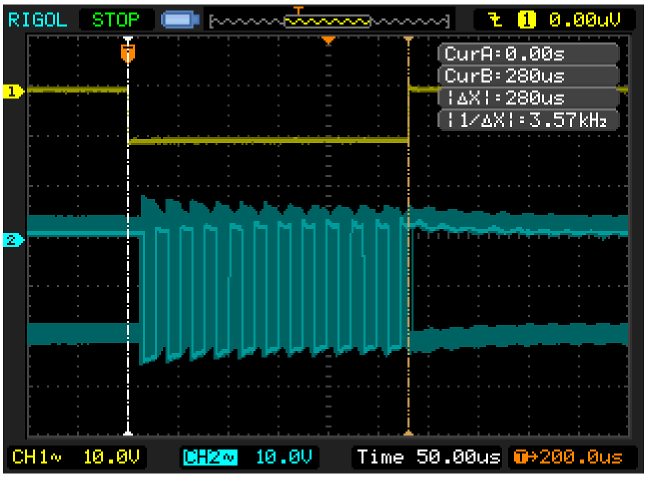


Figure 5-24 Actual Signal Generation Time

According to the block “Set Time Triggers” signal generation time should be 250µs. As Figure 5-24 shows, the time during which the signal generation is activated is 280µs which is exactly a multiple of the 70µs RTS time. As the Set Time Triggers block is always run at the same time during a RTS the relation between the time triggered interrupts and the next RTS where outputs are set stays constant. This is important because it shows that the time delay variation calculated from Figure 5-23 only stems from time delay variation and not from signal generation time variation. Also this static relation causes the time delay variance for the signal generation activation to be semi static – dependending on which total time delay is calculated according to the given distance, in this case the delay was $t_d = \frac{2}{344} * 1.5 - 422\mu = 8.299ms$ (with $422\mu s$ being the delay correction of that measurement) which is 118RTS and 39µs leading to a semi static delay of $70\mu s - 39\mu s = 41\mu s$. An additional variation comes from the time between signal generation activation and actual signal generation as shown in Figure 5-21 which contributes 12µs variation. The signal conditioning also contributes as signal amplification varies slightly leading to a possible variation by one period before the detection trigger level is exceeded causing a time delay variation of 25µs.

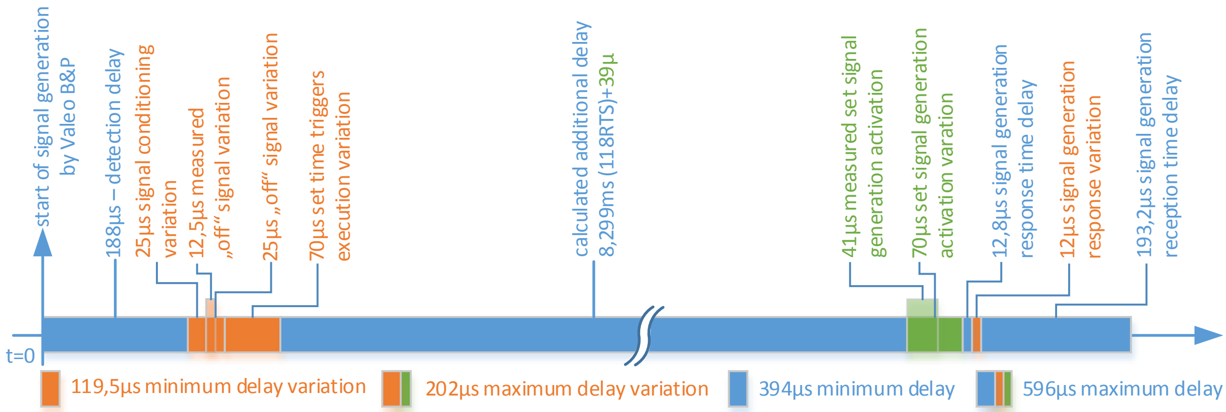


Figure 5-25 Static Delay – Blue, Delay Variance – Orange, Semi Static Delay Variance - Green

Figure 5-25 gives an overview of the contributors to the delay between signal generation and detection by Valeo B&P.

A possible way to reduce time delay variance below the suggested 58µs is to include time stamps. Here the time stamp from the edge detections would be compared to the system time and the time triggered interrupts would be set according to the real time step which is closest to the desired time delay and would reduce the maximum variance to $\frac{RTS}{2} = 35\mu s$. As the system time and the internal clock of the DS5001 are not synchronized a comparison can only serve to reduce variance, if carried out right after the interrupt is triggered. Unfortunately, the system time cannot be accessed inside an interrupt function. In order to eliminate these time delays the RTE will therefore need to be complied from C code. If configured in C code the D/A unit can be set to update values immediately from within an interrupt function, also the Set Time Triggers task could be executed directly without rate transition or with a rate transition but also with information about the system time and the time passed after the last detection. The signal generation will be constructed in a way which eliminates any pulses during the “off” state. This should allow the stimulation system to achieve a time delay variance of below 20µs only caused by varying function execution times.

5.4 Simulation Environment CarMaker

As example for sensor stimulation and its application an ultrasonic stimulation was integrated in a virtual vehicle test environment (CarMaker) for demonstrating a use case. CarMaker will only briefly be explained as a detailed description would exceed the size of this volume. In CarMaker street networks with traffic, simple geometric objects and a driver can be simulated. A sophisticated car model with an “IPG Driver” can be ordered to complete various tasks, such as parking in a parking spot. The interaction of an assistance system with the driver, the behavior of the driver, given data by an external assistance system, and various other verification and validation (V&V) scenarios can be executed with CarMaker. In this case the driver is set to drive, search for a parking spot and park in the found parking spot as shown in Figure 5-26 - Figure 5-30. The goal here is that the stimulated parking assistance system displays the same distance output as the rear right ultrasonic sensor measures.

Manöver

Nr	Start	Dauer	Längs	Quer	Marke/Beschreibung
	==== Globale Einstellungen ====				
0	0.0	-			
1	0.0	-	25		Searching for parking plac
2	0.0	6	stop		Stop for backward parking
3	6.0	-	back	-245	Backwards
4	6.0	-	back	300	Backwards
5	6.0	2	stop	0	Steer
6	8.0	-	3	0	Forward
7	8.0	0			Cleanup at end
8	8.0	==== ENDE ====			

Figure 5-26 Set of Commands for IPG Driver during the Test Scenario

Figure 5-27 Searching for a Parking Spot

Figure 5-28 Parking Spot found, Parking backwards

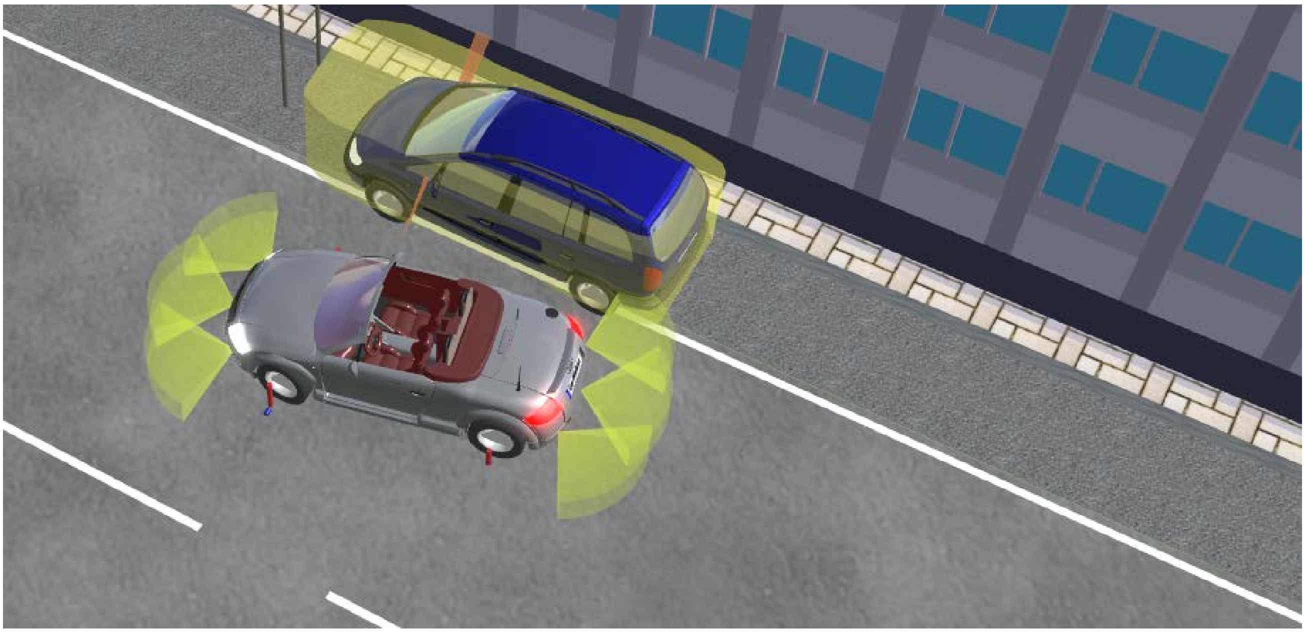


Figure 5-29 Parking backwards, the Rear Right Ultrasonic Sensor detects an Object

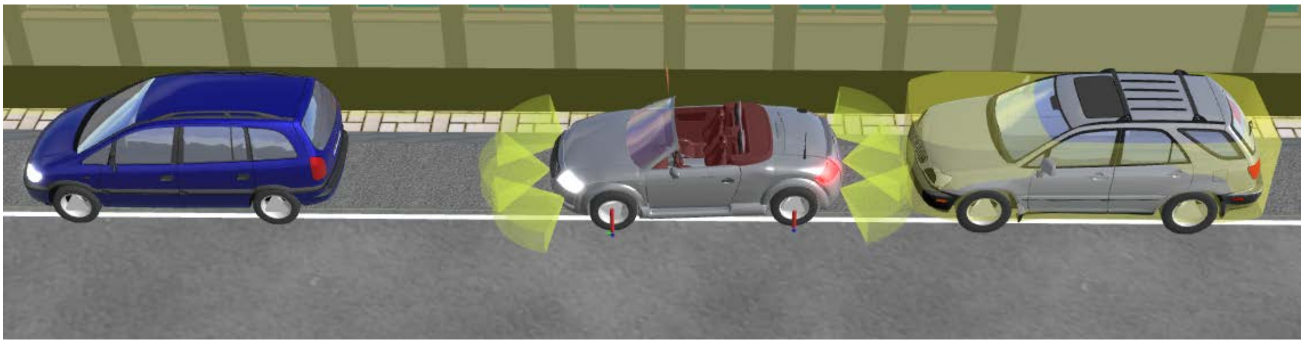


Figure 5-30 Driving into the middle of the Parking Spot, Rear Right Sensor detects an Object

CarMaker provides a separate object class for ADAS sensors. These sensors can be positioned on the chassis of a car and their field of view is adjustable. The sensor delivers a list of objects in the field of view including a relevant target which is always the one which is closest to the sensor as also shown in the excerpt of the CarMaker documentation (Appendix C). For these calculations all objects have a cuboid shape by default and a 2D plane projection is used for distance calculations. However, a custom shape as shown in Figure 5-31 can be defined which resembles the actual visualization more closely. The yellow highlighted space in Figure 5-27–Figure 5-30 shows which surface is used for the sensor distance calculations. The field of view of the ultrasonic sensors is also highlighted in yellow.

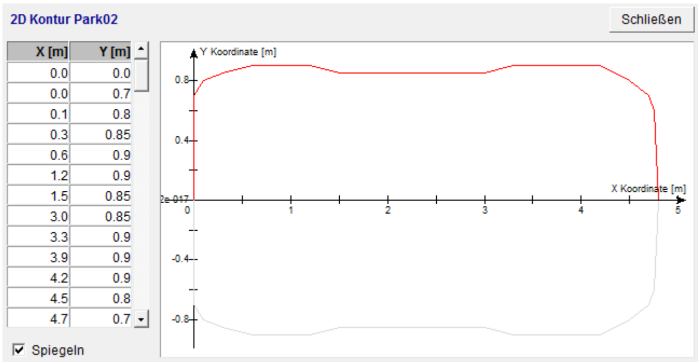


Figure 5-31 Custom Shape for CarMaker Objects

For objects within the sensor's field of view several quantities are provided, among them x,y,z and the shortest direct distance between the sensor and the reference point of an object as well as between the sensor and the nearest point of the surface of an object as described in the excerpt of the CarMaker documentation (Appendix B). Any of these quantities can be viewed in IPG Control. The "relevant target detected", the "distance to the nearest point of the relevant target" and the "relative velocity of the nearest point of the relevant target" of the rear right ultrasonic sensor during the parking maneuver are displayed in Figure 5-32.

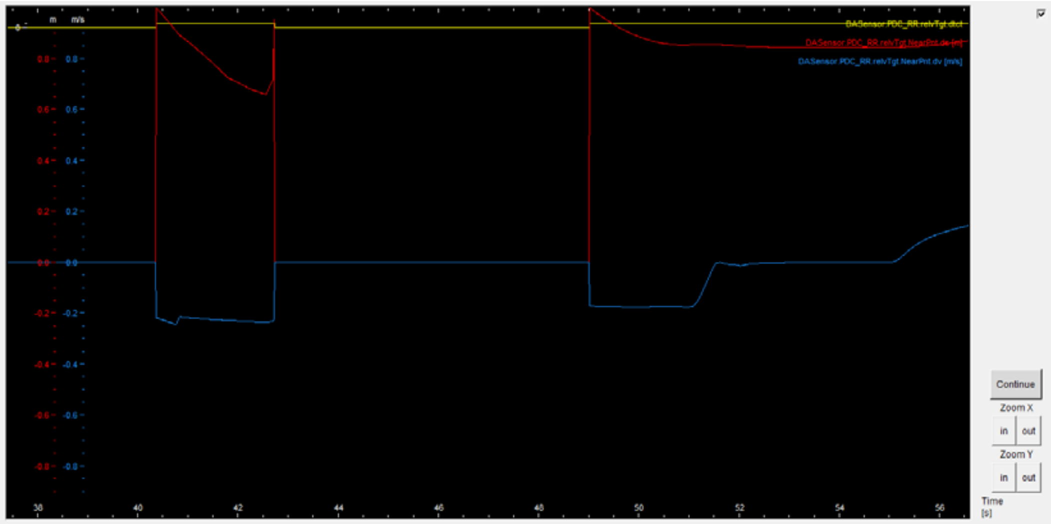


Figure 5-32 IPG Control, Target Detected, Distance and Velocity of Rear Right Ultrasonic Sensor

CarMaker provides Simulink blocks, which allow directly accessing the previously mentioned quantities during a use case run, and values from the simulation are updated every millisecond. Using these blocks the distance, velocity and target-detected variables are accessed as shown in Figure 5-34. The distance is then written to the RTE using the MATLAB – dSpace Interface Libraries (MLIB) provided by dSpace. Figure 5-33 shows how the whole stimulation system is set up.

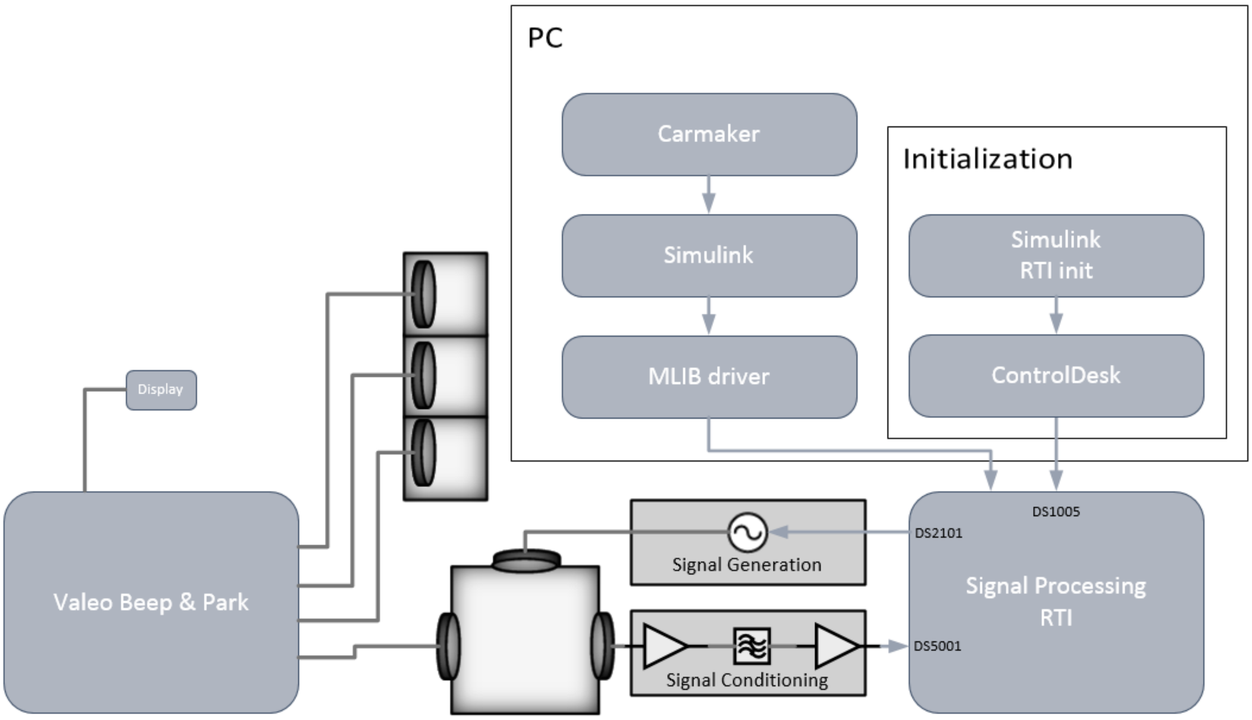


Figure 5-33 Ultrasonic Stimulation with Distance provided by CarMaker

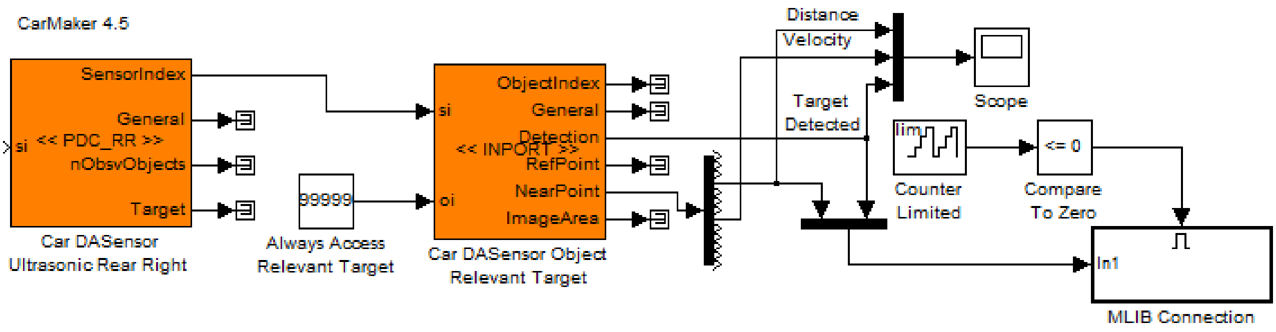


Figure 5-34 Simulink Model for Data Transfer from CarMaker to RTE

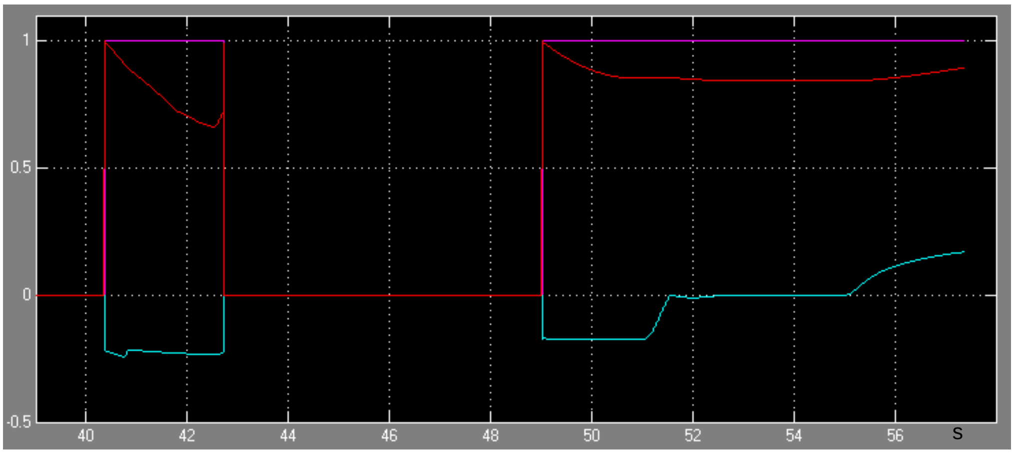
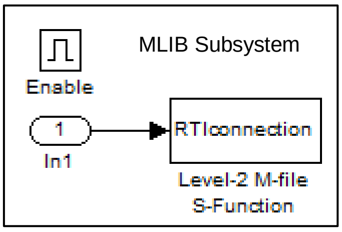


Figure 5-35 Simulink, Object Distance in Red, Velocity in Magenta and Relevant Target in Purple



The Distance and the Target Detected variable are provided to the MLIB subsystem which executes a Level-2 M-file S-Function block. This block in turn, starts the RTIconnection function (Appendix D) which uses the MLIB interface to write the current distance to the RTE, if “relevant Target” is set. MLIB was not designed to be executed within the Simulink framework and takes longer than 1ms to establish a data link and write data to the RTE. Since this function is executed within Simulink the whole simulation is halted until the writing process is finished which greatly decreases the speed of the CarMaker simulation. To limit the impact of this delay data is only written to the RTE every 27th step and only if a target is detected.

The MLIB block consists of two main parts: initialization and writing. In the initialization process the working conditions are verified. This includes checking whether the right program is loaded onto the RTE, the right board is connected and the application is running.

```
function Start(block)
    mlib('SelectBoard','DS1005');
    ApplName = ['C:\Users\u12z85\Documents\dSPACE\ControlDesk
    NG\4.1.0\Frequencyanalysis\Variable Descrip
    tions\frequencyanalysisv2.sdf\frequencyanalysisv2.ppc'];
    if mlib('IsApplRunning'), %check if an application is running
        ApplInfo = mlib('GetApplInfo');
        if strcmpi(ApplName,ApplInfo.name) ~= 1 %check if the right application
                                                 %is running
            err_msg = sprintf('*** This MLIB demo file needs the real-time pro
            cessor application\n*** ''%s'' running!',ApplName);
            error(err_msg);
        end;
    else %abort if no application is running
        err_msg = sprintf('*** This MLIB demo file needs the real-time processor
        application\n*** ''%s'' running!',ApplName);
        error(err_msg);
    end;
    global distance_desc;
    global k;
    k = 0;
    % Get handles for the distance(es)
    if isempty(distance_desc)
        variables = {'Model Root/Time-trigger set/Objektdistanz/Value'};
        distance_desc = mlib('GetTrcVar',variables);
    end
    %default setting: off
    simDistance = 1.8;
    mlib('Write',distance_desc,'Data', simDistance);
%endfunction
```

The writing part updates the variable object distance if “target detected” is set. If target detected is not set the distance is set to 1.8m again, which means the stimulation is always responding to a measurement pulse by the parking assistance system but only at a time where the response will not be measured when turned “off”.

```
function Update(block)

    simDistance    = block.InputPort(1).Data(1);
    targetDetected = block.InputPort(1).Data(2);
    global distance_desc;
    global k;
        %write current distance if target is detected
        if targetDetected ~= 0
            mlib('Write',distance_desc,'Data', simDistance);
            k = 1;
            %check if no target is detected and the distance has not yet
            %been reset to 1.8m
        elseif (targetDetected == 0) && (k == 1)
            simDistance = 1.8;
            mlib('Write',distance_desc,'Data', simDistance);
            k = 0;
        end
%endfunction
```

The Simulink blocks are updated every millisecond. This causes a distance error depending on the speed of the car. In full speed range active cruise control systems (FSRACC) ultrasonic distance measurement is used up to a speed of 20km/h to measure the distance of the car ahead. In this case the maximum distance error would be $20\frac{km}{h} = 5.56\frac{m}{s}$ $s_{\max} = 5.56\frac{m}{s} * 1ms = 5.56mm$ which is insignificant compared to the resolution of the system and therefore negligible. If updated only every 27th step, the maximum offset of the stimulation increases accordingly. The next version of the system will not transmit via the MLIB interface, but over CAN or Flex Ray which will eliminate this bottleneck.

6 Discussion and Outlook

The efforts to improve and make progress towards safety and autonomy of ADAS are currently increasing on a global scale. The innovations which are to come promise groundbreaking changes in transportation having the potential to influence our society as a whole. Test systems which are designed for verification and validation of such systems will gain importance along with the rising market share of ADAS. The prototype presented in this thesis will be developed further as part of the effort to establish an all-encompassing sensor stimulation vehicle in the loop test system. The next version of this prototype will be coded in C in order to allow the time triggers to be set directly from within the hardware interrupt, to enable and disable the hardware interrupt instead of setting and clearing the measurement variable and to also set the D/A board outputs directly. Signal generation will be built in hardware with an additional port to adjust the voltage for the signal generation. During signal generation the measurement will be disabled by hardware reducing the amount of computing power and interrupts required. Furthermore, the system will be enhanced in order to be capable of stimulating systems with cross detection capabilities and the MLIB interface will be replaced by CAN or Flex Ray which will allow distance updates every millisecond. Additionally the system will be expanded to 12 ultrasonic emulation units and a chassis mounting system will be implemented. To harness the new capabilities of the stimulation system an additional simulation on the basis of the 3D environment of CarMaker will be subject to research. Moreover, the research for this simulation will focus on providing amplitude information as well relevant reflections, especially critical measurement impairing echoes.

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[18] H. Winner, W. Wachenfeld, „Absicherung automatischen Fahrens", 6. FAS Tagung, Munich, November 2013

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[20] W. Lehfeldt, „Ultraschall kurz und bündig Physikalische Grundlagen und Anwendungen", Vogel-Verlag,ISBN 3-8023-0060-2, 1973

[21] http://en.wikipedia.org/wiki/Sound_pressure
http://de.wikipedia.org/wiki/Schalldruck

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10 Appendix

Summary of Levels of Driving Automation for On-Road Vehicles

This table summarizes SAE International's levels of *driving* automation for on-road vehicles. Information Report J3016 provides full definitions for these levels and for the italicized terms used therein. The levels are descriptive rather than normative and technical rather than legal. Elements indicate minimum rather than maximum capabilities for each level. "System" refers to the driver assistance system, combination of driver assistance systems, or *automated driving system*, as appropriate.

The table also shows how SAE's levels definitively correspond to those developed by the Germany Federal Highway Research Institute (BASt) and approximately correspond to those described by the US National Highway Traffic Safety Administration (NHTSA) in its "Preliminary Statement of Policy Concerning Automated Vehicles" of May 30, 2013.

Level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of *dynamic driving task*	System capability (*driving modes*)	BASt level	NHTSA level
***Human driver* monitors the driving environment**								
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a	Driver only	0
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes	Assisted	1
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes	Partially automated	2
***Automated driving system* ("system") monitors the driving environment**								
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes	Highly automated	3
4	**High Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes	Fully automated	3/4
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**	-	

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Appendix A

19.3 Object List

The CarMaker DASensor module provides for each configured s ensor a object list with quantities for each traffic obstacle relative to the view of the sensor

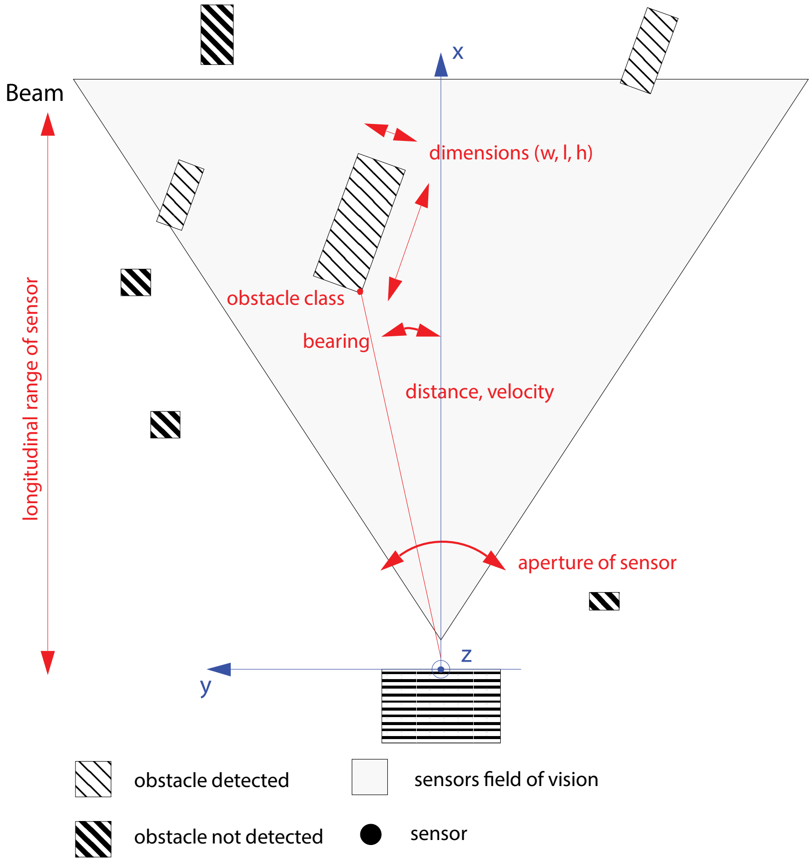

Figure 19.6: Object List

Available quantities in object list:

- object kind
- bearing (reference point and nearest point)
- relative distance and velocity (reference point and nearest point)
- relative orientation z-y-x (reference point)
- distance in x, y, z of sensor frame (reference point and nearest point)
- velocity in x, y, z of sensor frame (reference point and nearest point)
- flag: object is detected (in sensor vi ewing area)
- flag: object is in observation area
- incidence angles between the sensor beam and the object
- width, height, length of object and height ab ove ground

Appendix B

19.5.1 Closest Object

Each sensor can detect a closest object.

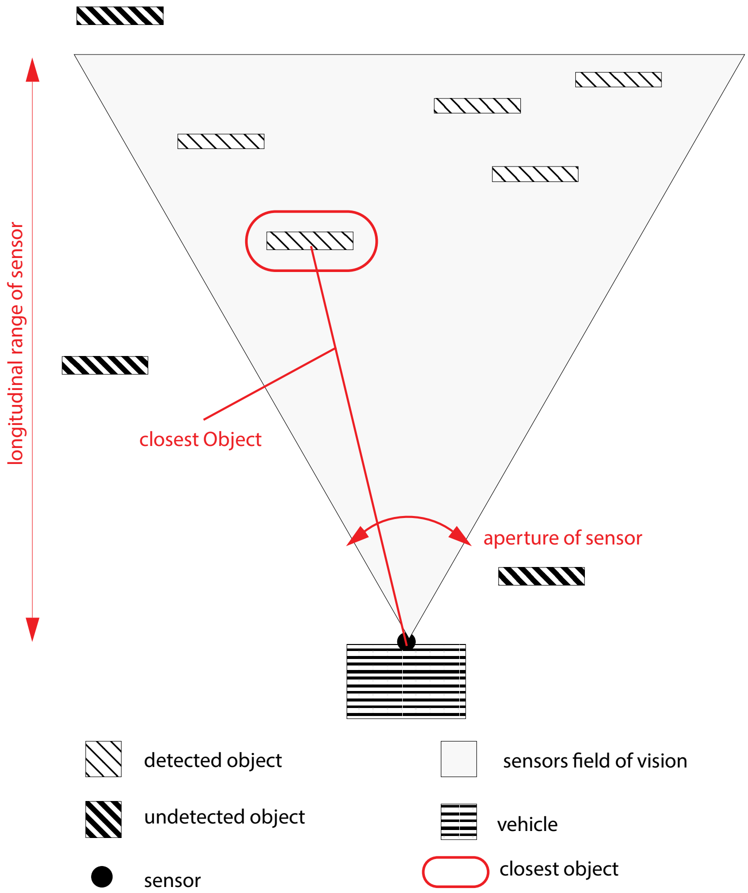

Figure 19.10: Finding closest object

The sensor module iterates in each time step over all objects to find the closest object and calculates the distance from this object to the sensor. Depending on the calculation class the distance is referring to the reference point (CalcClass = ReferencePoint) or the nearest point (CalcClass = NearestPoint or ImageArea). The object with the smallest overall distance is the relevant target.

If two or more objects have the same distance, the first detected object will be taken into account.

Appendix C

The Code of the function RTIconnection.m

Appendix D

```
% ---------------------------------------------------------------------------
% RTIconnection
% Write the distance of the nearest Object from IPG Carmaker to the RTI
% Ultrasonic Stimulation.
%
% Before invoking this M-file the application Ultrasonic Stimulation must
% be running on the Real Time Environment from dSpace
%
%----------------------------------------------------------------------------
function RTIconnection(block)
  %Bulds up a connection to the Real Time Environment and allows
  %modification of any variable
  setup(block);
%endfunction

function setup(block)

  % Register number of input and output ports
  block.NumInputPorts  = 1;
  block.NumOutputPorts = 0;

  % Setup functional port properties to dynamically
  % inherited.
  block.SetPreCompInpPortInfoToDynamic;
  block.SetPreCompOutPortInfoToDynamic;
  block.InputPort(1).DirectFeedthrough = true;

  % Set block sample time to inherited
  block.SampleTimes = [-1 0];

  % Set the block simStateCompliance to default (i.e., same as a built-in block)
  block.SimStateCompliance = 'DefaultSimState';

  % Run accelerator on TLC
  block.SetAccelRunOnTLC(true);

  %% Register methods
  % Start:
  %   Functionality    : Call to initialize the state and the work
  %                      area values.
  %   C-Mex counterpart: mdlStart
  %
  block.RegBlockMethod('Start', @Start);
  % Update:
  %   Functionality    : Call to update the discrete states
  %                      during a simulation step.
  %   C-Mex counterpart: mdlUpdate
  %
  block.RegBlockMethod('Update', @Update);
%endfunction

function Start(block)
    mlib('SelectBoard','DS1005');
    ApplName = ['C:\Users\u12z85\Documents\dSPACE\ControlDesk
    NG\4.1.0\Frequencyanalysis\Variable Descrip
    tions\frequencyanalysisv2.sdf\frequencyanalysisv2.ppc'];
```

```
    if mlib('IsApplRunning'), %check if an application is running
        ApplInfo = mlib('GetApplInfo');
        if strcmpi(ApplName,ApplInfo.name) ~= 1 %check if the right application
                                                %is running
            err_msg = sprintf('*** This MLIB demo file needs the real-time pro
            cessor application\n*** ''%s'' running!',ApplName);
            error(err_msg);
        end;
    else %abort if no application is running
        err_msg = sprintf('*** This MLIB demo file needs the real-time processor
        application\n*** ''%s'' running!',ApplName);
        error(err_msg);
    end;
    global distance_desc;
    global k;
    k = 0;
    % Get handles for the distance(es)
    if isempty(distance_desc)
        variables = {'Model Root/Time-trigger set/Objektdistanz/Value'};
        distance_desc = mlib('GetTrcVar',variables);
    end
    %default setting: off
    simDistance = 1.8;
    mlib('Write',distance_desc,'Data', simDistance);
%endfunction

function Update(block)
    simDistance    = block.InputPort(1).Data(1);
    targetDetected = block.InputPort(1).Data(2);
    global distance_desc;
    global k;
        %write current distance if target is detected
        if targetDetected ~= 0
            mlib('Write',distance_desc,'Data', simDistance);
            k = 1;
            %check if no target is detected and the distance has not yet
            %been reset to 1.8m
        elseif (targetDetected == 0) && (k == 1)
            simDistance = 1.8;
            mlib('Write',distance_desc,'Data', simDistance);
            k = 0;
        end
%endfunction
```