Master's Dissertation in Mechanical Engineering on:

Cleaning System for LiDAR AV Sensor

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"Pelo sonho é que vamos,
Comovidos e mudos.
Chegamos? Não chegamos?
Haja ou não frutos,
Pelo Sonho é que vamos.
Basta a fé no que temos.
Basta a esperança naquilo
Que talvez não teremos.
Basta que a alma demos,
Com a mesma alegria,
Ao que desconhecemos
E ao que é do dia-a-dia.

Chegamos? Não chegamos?

- Partimos. Vamos. Somos."

Sebastião da Gama, *O Sonho*

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Resumo

Solução de Limpeza para Sistema LiDAR

A mudança do paradigma da condução está cada vez mais próxima. Nos últimos anos, Original Equipment Manufacturers (OEMs) e fornecedores dedicam-se à investigação e investimento tanto em hardware como software capazes de suportar e viabilizar esta transformação. Sabe-se que será inevitável mas, no entanto, o desenvolvimento pleno está ainda a alguns anos.

Esta dissertação vem no seguimento de um projeto de Inovação da Bosch, com o objetivo de criar uma solução para um dos problemas mais críticos da conduçaõ autónoma: a limpeza do LiDAR, sensor que a torna possível.

Assim, numa primeira fase, após pesquisa acerca do estado de arte deste segmento, foi elaborado um protótipo. Esta solução de limpeza foi incorporada no conceito já definido pela Bosch, 'Rotating Housing'. Este conceito, ainda que apresente alguma flexibilidade em alguns parâmetros, conta com algumas caraterísticas pré-definidas. O housing, com componentes óticos, eletrónicos e mecânicos, roda sobre o suporte lateral, cuja função será principalmente estrutural e de fixação no veículo.

Depois de desenvolvida a solução de limpeza ativa, o foco passa a ser a solução passiva, ou seja, tornar a interface entre o exterior e o interior do LiDAR, a *Protective Optical Window* (POW), o mais repelente à poluição possível. Como componente experimental e, para a seleção do material da mesma, foram realizados testes, nomeadamente, à transmissão para eleição do material para a POW, testes de poluição e aerodinâmica e, por fim, testes de ângulo de contacto com a água.

Finalmente, com a solução de limpeza ativa e passiva desenvolvida, procedeu-se à sua integração no housing, desenvolvido em paralelo pela minha colega Carolina Cunha. Em sumário, o objetivo da dissertação de criar um sistema de limpeza capaz de preservar os propriedades óticas, de forma a garantir a maior trasmissão possível através da POW, e integrá-lo no housing desenvolvido em paralelo foi concluído com sucesso, com a obtenção de um protótipo físico e a eleição do policarbonato Makrolon 2407 como material da POW.

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Abstract

Cleaning System for LiDAR AV Sensor

The paradigm shift for driving is getting closer and closer. In the last few years, Original Equipment Manufacturers (OEMs) and suppliers have dedicated themselves to research and investment in both hardware and software capable of connecting and enabling this huge transformation. It is known that it is inevitable but, however, full development and readiness is still a few years away.

This dissertation follows Bosch's Innovation project, with the goal of creating a solution to one of the most critical problems of autonomous driving: cleaning the LiDAR, sensor that makes it possible.

Thereby, in a first phase, after researching the state of the art of this segment, a prototype was designed. This cleaning solution has been incorporated into the concept already defined by Bosch, 'Rotating Housing'. This concept, although presenting flexibility in some parameters, has some pre-defined features. The housing, with optical, electronic and mechanical components, rotates on the side support, whose function will be mainly structural and, to fix it to the car. After developing the active cleaning solution, the focus becomes the passive solution. In other words, the goal becomes making an interface between the exterior and interior of LiDAR, the *Protective Optical Window* (POW), as repellent to pollution as possible. For the selection of the material, some tests were carried out: transmission - to choose the material with the most suitable properties for the purpose for which it is intended - aerodynamic and pollution tests and, finally, water angle contact (WCA) tests. Finally, with the cleaning solution active and passive developed, this was integrated into the housing, developed in parallel by my colleague Carolina Cunha. In summary, the goal of the dissertation: to create a cleaning system capable of maintaining the desirable optical properties in order to guarantee the greatest possible transmission through the POW and integrate it in a housing, developed in parallel, was successfully completed, having obtained a physical prototype and the choice of a polycarbonate, Makrolon 2407, as the material for the POW.

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Em primeiro lugar, gostaria de agradecer ao meu orientador, Marco Parente, que me confirmou que tinha feita a escolha mais acertada. Pelo seu profissionalismo, boa disposição e positivismo nestes meses. Ao co-orientador, professor Abílio de Jesus, por ter sido sempre presente e disponível e uma mais-valia pelos conhecimentos trasnmitidos. Sem dúvida, uma dupla de orienradores imbativel.

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Ao meu mentor, Engº. Bruno Lopes, agradeço verdadeiramente a paciência diária, disponibilidade total e constante e tranquilidade que me transmitiu nos últimos seis meses. Não poderia pedir melhor professor. Ao co-mentor, Engº. João Santos, um obrigada por me ensinar o que é ser um engenheiro mecânico na vida real e, sobretudo, a importância da epoxy. Deixamos o fish.term para não perderem o hábito e continuarem a ser os melhores mentores.

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Ao João, pelo abraço e sorriso sempre à minha espera. Pelo amor.

À minha família, em especial aos meus pais, João e Marcelina, pelo o amor incondicional, por fazerem tudo por mim e por serem a minha maior motivação. Aos meus avós, madrinha e tia Lúcia. Em particular, ao meu avô José. Espero que esteja orgulhoso. Aos meus avós. Ao meu irmão João, que, não me facilitando a vida, me ajudou a preseverar.

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Notation

Abbreviations

AVs	Autonomous Vehicles
AD	Autonomous Driving
ADAS	Advanced Drive
EDS	Energy-dispersive X-ray spectroscopy
FoV	Field of View
FSD	Full Self Driving
HW	Hardware
LiDAR	Light and Detection Ranging
SAE	Society of Automotive Engineers
NIR	Near-Infrared
UV	Ulra Violet
POW	Protective Optical Window
KPI	Key Performance Indicator
SW	Software
OEM	Original Equipment manufacturer
OS	Operating System
US	United States

Symbols

d	Distance [m]
c	Light speed in vacuum [m/s]
v	Light speed in the atmosphere [m/s]
v	Frequency [Hz]
n	Refractive index
λ	Wavelength [nm]
h	Plank constant
h_c	Photon energy
I_0	Incident Light
R	Reflected quantity of light
D	Dispersed quantity of light
A	Absorbed quantity of light
T	Transmitted quantity of light
$R_{diffuse}$	Diffused Reflection
$R_{specular}$	Specular Reflection
I	Light Intensity

x	Material Thickness
α	Absorption coefficient
TIS	Total Integratted Scattering
r_s	Specular Reflection of smooth surface
r_0	Specular Reflection of rough surface
TPX	PXMethylpentene
NAS	Blend of acrylic and styrene

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Chapter 1

Introduction

In Chapter 1.1, BOSCH GROUP is presented as a company, specially within Portugal. The motivations are addressed in Section 1.2, while the main goal is summarised in Section 1.3. In this Chapter, we also present and discuss the structure of the document in Section 1.4. Finally, we must refer that a compilation of the notation introduced throughout this dissertation is located before the beginning of this Chapter.

1.1 Company Introduction

Founded in 1886 by Robert Bosch, Robert Bosch GmbH is a multinational engineering company based in Gerlingen, Germany. Bosch, with locations in 60 countries, currently, focus its work on mobility solutions, industrial technology, energy and consumer goods.

In Portugal, Bosch has been present since 1911, currently having facilities in Aveiro, Bosch *Termotecnology*, in Ovar, Bosch *Security Systems*, and in Braga, Bosch *Car Multimedia*. In total, the company has over 5300 employees in Portugal (February 2018), having generated, in 2018, more than 1.5 billion euros in sales [1].

Bosch *Termotecnology*, in Aveiro, provides hot water solutions through heaters, boilers and heat pumps. In Ovar, video surveillance and communication systems are developed. Finally, in Braga, Bosch *Car Multimedia* is in charge of the production of *infotainment* systems (*Information and entertainment*), instrumentation and safety sensors for the automotive industry. The company's Portuguese headquarters is located in Lisbon, where sales, marketing and accounting activities are carried out, however, all development and production units are located in Aveiro, Ovar and Braga, and currently exports 95% of products developed for international markets [1].

With around 3500 employees, Bosch *Car Multimedia*, in Braga, has one of Bosch's research and development centers, being responsible for several innovation projects. One of the divisions that constitutes the research and development center of Braga is the CC (*Chassis Systems Control)* division, which is responsible for the development of active and passive safety and driver assistance systems. It is in the PS business unit (*Passive Systems*), belonging to the CC division, that the project under study is being developed.

1.2 Motivation

Since its inception, the automobile has been a flashpoint for technological, economic, and social innovation, doing as much as any human invention to change how people live [2]. As autonomous-driving technology advances, new transportation use cases will emerge, largely driven by factors such as what is transported, type of vehicle ownership, and where the vehicle operates. Our mental models about mobility—individually owned cars, gas stations, traffic jams, the driver's license as a rite of passage are on the verge of disruption. Mobility is about to become cheaper, more convenient, a better experience, safer, and cleaner, not 50 or even 25 years from now, but perhaps within a dozen [3].

It is a relatively safe bet, for example, that Autonomous Vehicles (AVs) will give rise to new business models — and change existing ones — within the transportation sector once they become prevalent. The array of sensors and software that will allow these vehicles to navigate streets and highways with little to no engagement from a human driver are tremendously expensive today and will continue to add greatly to the cost of cars or trucks equipped with them for the foreseeable future. Such vehicles will, likely, remain out of reach for the average car buyer for a fair bit of time. Instead, we expect AVs to be very attractive to ride-hailing operators, since they will both reduce labor costs and increase asset utilisation. However, due to their significantly higher upfront cost compared with traditional vehicles, we expect that most AVs will be purchased (at least initially) by companies that manage large fleets. Automotive companies, such as Bosch, have already begun to invest in this future, laying the groundwork through bets on software and sensor technology. These investments are helping the change and evolution in the structure of the automotive industry that will have long-lasting consequences and for which auto companies must prepare [2] [4] [5].

The question facing auto companies today is whether they should embrace their current strengths or seek to reposition themselves in the value chain. It should be pointed out that there are few examples of companies successfully "doing it all." As an example, airframe makers do not also manufacture avionics or jet engines, neither they operate airlines. The ecosystem of the semi-autonomous and autonomous vehicles consists of manufacturers such as *Volkswagen* (Germany), *Daimler* (Germany), *Nissan Motor* (Japan), *Google* (US), *Cisco Systems* (US), *Tesla* (US), and *Visteon* (US) and suppliers such as *Continental* (Germany), *Robert Bosch* (Germany), *Delphi Automotive* (UK), *Denso* (Japan), and *Valeo* (France). Thus, Bosch goal is not the creation of an Autonomous Vehicle but rather the SW and HW for them.

PwC analysis found that US investment in private mobility companies over the last five years totaled $6.8 billion in the 2012-2017 period - with $2.6 billion invested in companies developing technology supporting autonomous passenger vehicles development (self-driving autos) and $4.2 billion in companies focused on technology for broad-use, non-auto autonomous mobility [6].

Recent developments in autonomous vehicle instrumentation have led to advancements in laser-based LiDAR sensors. For these type of systems, sensor performance is dependent on fast response time and good contrast at long distances. Careful design for the optical transmitter assembly is paramount to achieving good device performance, and has become a primary differentiating factor between emerging LiDAR technologies. An autonomous car whose sensors are compromised cannot perform its job. In harsh and difficult weather conditions, contaminants like water or particles from the road tend to attach on the outer surfaces of a vehicle. This applies to the sensor systems of the vehicle as well. This is one of the reasons why they need to be separated from the environment with a protective optical window (POW). In order to provide a good visibility in all conditions and for an infallible security, sensors must be perfectly clean, including the LiDAR.

In this work, the proposal is to create a active/passive cleaning solution for the LiDAR system and then apply it to a specific housing, which will also be developed in a parallel study, conducted at the same time inside the same work team.

1.3 Main Goal

The main purpose of this work is to create, design and engineer an active/passive cleaning solution for the protective optical window, the interface between the optical system of Bosch's LiDAR and the environment. Additionally, another challenge will be the merge with the new housing, which will be carried out in parallel within the same work team by my fellow colleague, Carolina Cunha.

It is important to remark that there are, already, several studies on the development of cleaning solutions. However, the biggest challenge in this project will be the fusion between the new concept for the housing and, besides that, the attempt to build something that, in the future, could be, effectively, employed in the automotive market.

A meaningful point to make, however, is that our intention in this dissertation goes well beyond the simple projection of a possible solution, but rather the seeking for a complete system more compact than what already exists which could be placed in less conspicuous places such as in the vehicles bumper and body panels, instead of mounted on the roof.

On the whole, we expect that this work might spur further improvements in effective solutions for a good performance of Bosch´s LiDAR System.

1.4 Outline

In this Section, the contents of the remaining Chapters of this document are summarised.

Chapter 2 - Aims to give the reader an insight into the workflow, as well as the theoretical and practical methods used within this thesis. Also provides the reader with information about the tools to be used during the thesis's work.

Chapter 3 - Intends to introduce the reader to appropriate information about the relevant technologies and topics applied in this thesis. The chapter starts with a Literature Review about Advanced Driver Assistance Systems, Automotive Sensors and Levels of automation. A market analysis in automated driving is also presented. A description of the LiDAR technology comes ahead. This is followed by an explanation of the optical system inherent to the LiDAR system and light propagation. Finally, a section regarding relevant regulations and specifications affecting the system is also provided.

Chapter 4 - Summarises several automotive suppliers and OEMs that have created their own patents detailing several methods of cleaning of opto-mechanic sensors.

Chapter 5 - Explores the problem of surface contamination of cars, which represents a major engineering challenge to vehicle manufacturers, operators and users. The focus of this Chapter relays on an **Environment Analysis**, more precisely, which conditions may a car be exposed to, Section 5.1; in Section 5.2, **Pollution Detection**, understand how can that pollution be detected by the car in order to activate the cleaning solution for the LiDAR System. Finally, in Section 5.3, **Types of Pollution**, considering the Environment Analysis previously done, the goal is to study the possible contaminants to which a car may be exposed.

Chapter 6 - Aims to exhibit the progress and results obtained through the concept development phase of the thesis. The practical part of this thesis is divided into two parts: the first part corresponds to the development of the active solution. The second part corresponds to the characterisation of promising materials for the POW. The concept development phase followed the research phase.

Chapter 7 - Aims to provide the reader with information about the testing of the POW. The chapter begins with a introduction to materials chosen for testing, the explanation of the different tests, setups and results.

Chapter 2

Methodology

The following chapter aims to give the reader an insight into the workflow, as well as the theoretical and practical methods used within this thesis. This chapter also provides the reader with information about the tools to be used during the thesis's work.

2.1 Workflow

In this section, the description and overview of the different activities in the project and how much time was spent on them will be presented. The milestones, set before the project started, are also presented here. Finally, a Gantt chart of the global distribution of activities through the course of time s also shown in Appendix A.

2.1.1 Project Preparation and Planning

The initial phase of this dissertation, Chapter 3 was dedicated mainly towards literature research. The researched areas were: *Advanced Driver Assistance Systems (ADAS) and Automotive Sensors*, *Levels of Automation*, *Off-Road Versus Highway and City Driving*, *LiDAR Technology*, *Market analysis in automated driving*, *Optical System* for a LiDAR sensor, *Propagation of light in LiDAR operation* and *optical materials and properties.*

This dissertation project consisted in several phases: preparation, prototype development, prototype assembly, prototype testing and, finally, delivery. Preparation activities included planning out the project and researching about the state of art of all the topics previously mentioned in the last paragraph.

The research and knowledge gathered was mainly based in Bosch's documents, deliverables and patents.

The activities, included in the *Prototype Development* phase, included *Concept Generation*, *Generation and Description of Concepts*, *Screening and Concept Selection* and *Prototype Design*.

The structure of the dissertation was planned by specifying critical deadlines and milestones, as well as grouping the project into distinct phases.

2.2 Tools

The tools that will be used to accomplish the thesis work is presented in this section.

2.2.1 Siemens NX Unigraphics

Siemens NX is a software that is specifically designed to aid in the all aspect of designing a product. Among other possibilities, in this dissertation it will be used to design and 3D modeling all the prototype components. It was also used to obtain the 2D drawings of each component.

Chapter 3

Literature Review

This chapter intends to introduce the reader to appropriate information about the relevant technologies and topics applied in this thesis. The chapter starts with a Literature Review about Advanced Driver Assistance Systems, Automotive Sensors and Levels of automation. A market analysis in automated driving is also presented in this Chapter. A description of the LiDAR technology comes ahead. This is followed by an explanation of the optical system inherent to the LiDAR system and light propagation. Finally, a section regarding relevant regulations and specifications affecting the system is also provided.

3.1 ADAS and Automotive Sensors

For many years now, drivers of passenger cars and commercial vehicles have widely accepted driving safety systems and advanced driver assistance systems (ADAS) as devices assisting them in road traffic. Today's vehicles contain up to 100 control units, most of them in the field of engine management. Their safety potential has been proven many times over in studies and practical trials. A large number of driver assistance systems is available for almost all vehicles. They ensure stability in critical situations, maintain a safe distance to the vehicle in front, and support the driver while parking. Monitoring the surroundings in all directions requires data and information from the vehicle's sensors, e.g. ultrasound, radar, cameras [7].

The capabilities of the sensors and the data processing by the control units are continually growing, and highly advanced software is used to analyse this information in fractions of a second. The complete suite of 3D sensing technologies in use for autonomous vehicles includes:

- **Radar sensors**, which are usually located in the front and rear of the vehicle can detect other vehicles and obstacles. The rear sensor detects traffic approaching from behind and vehicles that are overtaking. The traffic in front is monitored by long-range radar. The short-range radar surveys the vehicle's immediate surroundings. Used for detection, localisation and tracking (range and velocity) of objects using radio waves. Performs very well in extreme weather conditions and at long distances (200 meters), compararing to cameras for example.

- **Cameras** are used, for instance, to recognise lane markings, traffic signs, traffic lights, and other road users.
- **Ultrasound sensors** help drivers manoeuvre into parking spaces, serving the same purpose as (a substitute for) short-range radar.
- **LiDAR**, which will be explained later in this document.

In the past, radar, cameras, and ultrasound sensors were used for separate functions, however, now, all the relevant data can be linked intelligently and simultaneously by sensor fusion, which makes automated driving possible in the first place [8] [9]. A scheme with all these features is presented in Figure 3.1.

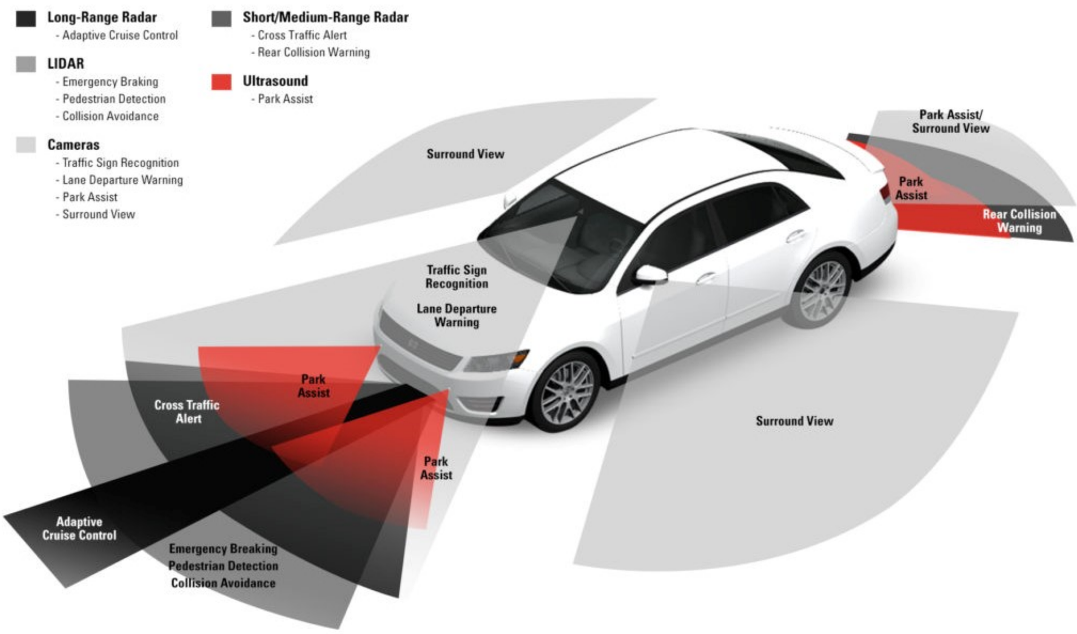

Figure 3.1 Features of *Advanced Driver Assistance Systems* [7].

3.1.1 Levels of Automation

The Society of Automotive Engineers (SAE) defines 6 levels of driving automation ranging from 0 (fully manual) to 5 (fully autonomous), as shown in Figure 3.2.

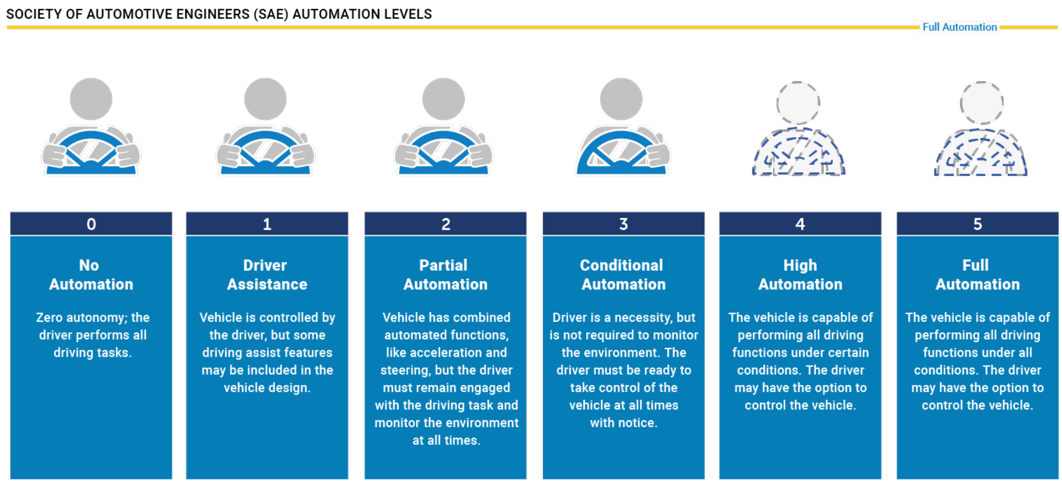

Figure 3.2 SAE Levels of Driving Automation [10].

With these concepts in mind, the six SAE Levels of Driving Automation are as follows:

Level 0 – These vehicles have no automation features at all. These are most likely older or more basic cars.

Level 1 - Cars that fall into this category possess some low-level driver assistance features. Vehicles with features that stop them from leaving a highway lane unexpectedly (*Lane departure assist*), or allow them to follow traffic at a safe distance (*Adaptive cruise control*) fall into this category. Therefore, level 1 features tend to be positioned as driver aids or safety features.

Level 2 - At Level 2 autonomy a car can drive itself. But even so, drivers of such cars should always pay full attention to the road. *Tesla's Full Self-Driving Autopilot* system is generally considered a Level 2 piece of technology. When Full Self-Driving is engaged on a *Tesla*, the vehicle can change lanes, navigate, and speed up and slow down, without driver intervention. However, the driver must still hold the steering wheel, and monitor traffic for safety. Many refer to Level 2 features as *Advanced Driver Assistance Systems* or *ADAS*.

Level 3 - Level 3 vehicles are generally thought to be properly autonomous vehicles that can interpret the world around them without human intervention. In theory, Level 3 vehicles should be good enough that the driver does not need to pay full attention to the road. But they should still be there ready to take over when needed. Of course, local laws also dictate what level of attention the driver should be paying to the road.

Level 4 - Vehicles in this category are so capable of driving themselves that they technically need no driver at all. There are often geographical restrictions on where this self-driving tech can be used, so drivers are still needed. Level 4 vehicles often also have their top-speeds limited, and can only driver faster under the control of a human. Projects like Google's Waymo is one of the most well-known applications of Level 4 Self-Driving tech.

Level 5 - This is the e pinnacle for developers of self-driving tech. In Level 5 vehicles, no driver is needed, cars will be totally autonomous, with no restrictions over where they can go. In theory, Level 5 autonomous self-driving vehicles will blend seamlessly into traffic. For passengers, they will be able to tell the car where they need to go, and leave the rest to the vehicle [7] [11] [10].

Making the bridge between the SAE classification and what already is forecasted, *McKinsey* research suggests that by 2030, 45 percent of new vehicles will reach the third level of connectivity, representing a value pool ranging from $450 billion to $750 billion [3].

A brief location overview in the car with the placement of radar, cameras and LiDAR for each level of automation is presented in Figure 3.3.

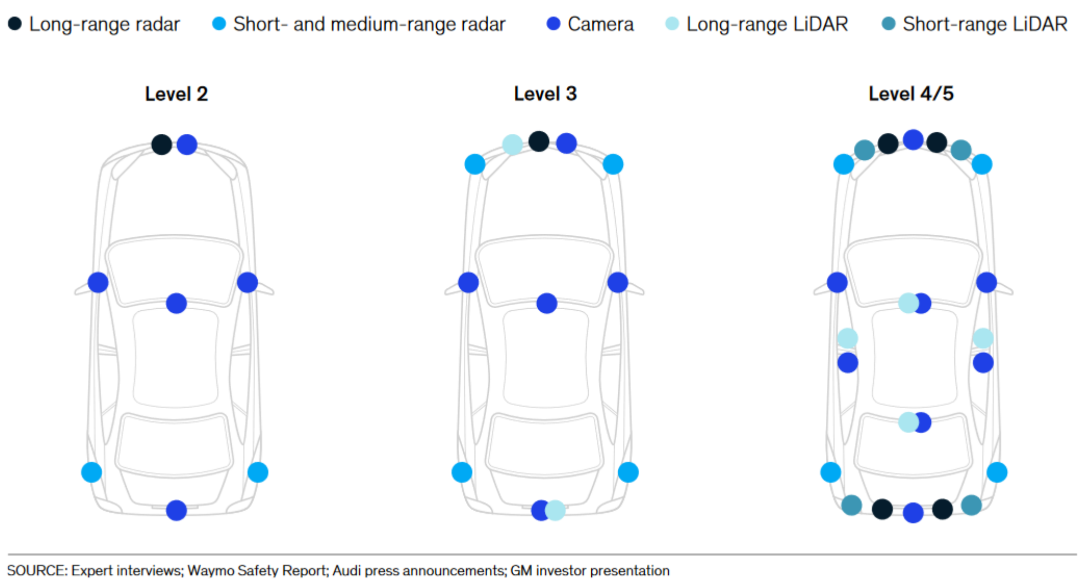

Figure 3.3 Sketch of a vehicle and its sensor setup for AD [3].

3.1.2 Off-Road Versus Highway and City Driving

Of course, there are many differences between off-road, fully autonomous desert racing, on-road highway and urban driving, although a number of parallel challenges can also be identified. Robustness and safe performance of hardware and software is obviously required for both off-road driving and production automobiles. Certain problems are mitigated when a system is designed for a passenger vehicle environment.

The automated driving functions include "*Highway Driving*," which in the case of highly automated driving will be used up to a defined speed on highways and similar roads. The driver can choose when to activate the system and does not have to monitor it continuously. This takes away some of the stress of driving, and in certain situations they will be prompted in good time to resume the task of driving. *Highway driving* is a much more structured environment than off-road racing, and that structure can be exploited in sensor and control system design [12].

On the other hand, the *Urban environment*, which may consist of irregular and changing road networks and vehicles and pedestrians behaving unpredictably, is much less structured than highway driving and may require significantly more sensing capabilities. Redundancy of sensing modalities is required, especially in a less structured environment [12].

In a practical way, these systems provide precise and accurate co-ordinate measurement data that is used to create realistic and detailed 3D city models viewable from street-level. For each driving environment a certain level of automation and features associated are requested, as shown in Figure 3.4.

Figure 3.4 Automation Evolution [10] [7].

3.2 LiDAR Technology

Light Detection And Ranging **(LiDAR)** is an optical measurement principle to localise and measure the distance of objects in space. Basically, it is similar to a Radar system, mentioned in Section 3.1, however, instead of using microwaves, LiDAR uses ultraviolet, infrared or beams within the visible light spectrum [8] [13].

Scientists have used lasers to measure distances shortly after the advent of the laser in 1960. In 1969, the Laser Ranging Retro reflector was deployed on the surface of the Moon by the Apollo 11 Mission. Neil Armstrong and Buzz Aldrin during their historic moonwalk on July 20, 1969, deployed a 46cm square laser retro reflector array containing 100 corner cube reflectors and on August 1, 1969, a laser pulse aimed through the lens of the 3-meter telescope at California's Lick Observatory successfully hit the array for the first time. By measuring the time it took for the beam to perform the round trip (about 2.5 seconds) the distance between the Earth and the Moon was calculated with an uncertainty of ± 25 centimetres. Two years later, the first space-borne lidar was launched aboard Apollo 15. Using a 694nm ruby laser operating at a rate of 0.05 Hz, the so-called Apollo Laser Altimeter mapped the elevation profile of the Moon's surface for the first time [8].

Besides distance measurements, which is the basic task, LiDAR sensors can be used for a limited visual detection of objects by analysing the light intensity, visibility measurement by analysing the shape of the reflected LiDAR pulse, day/night detection as background illumination is significantly different between day and night, pollution detection and speed estimation. As several companies increase the research in topics for autonomous driving vehicles, namely LiDAR - as basis sensor technology for scanning the environment - there is an increase in development activities for LiDAR sensors meeting automotive requirements (cost, performance, reliability) and the market around them[13].

The LiDAR sensor is also characterised by having a high resolution, wide angle, and high accuracy due to active distance measurement, which will be needed to detect and classify objects or track landmarks for localisation [5].

3.2.1 Market analysis in automated driving

Several studies have been performed to predict the market share in sales of fully or partially AVs in the future. In this article, fully AVs include level 4 or 5 cars and levels 1 to 3 are collectively called partially AVs, according to SAE International standards. Figure 3.5 and Figure 3.6 summarise the forecasts from different entities, including consulting firms and researchers for fully autonomous vehicles sales and for partially autonomous vehicles sales, respectively. In all predictions, fully AVs will enjoy a consistent growth, and the share of partially AVs may increase first and then decrease. Most of the studies are based on the U.S. case (Chen et al; Fox-Penner et al; Litman), as seen in Figure 3.5. Certain studies forecast the global trend (Mosquet et al.; McKinsey&Company; Laslau et al.) [14], as seen in Figures 3.5 and 3.6.

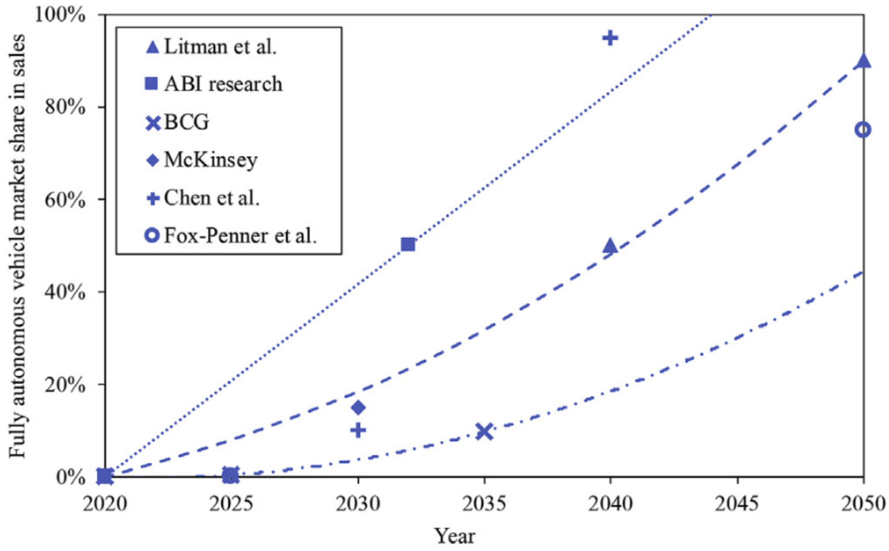

Figure 3.5 Predictions for *Fully autonomous* vehicle market share in sales [14].

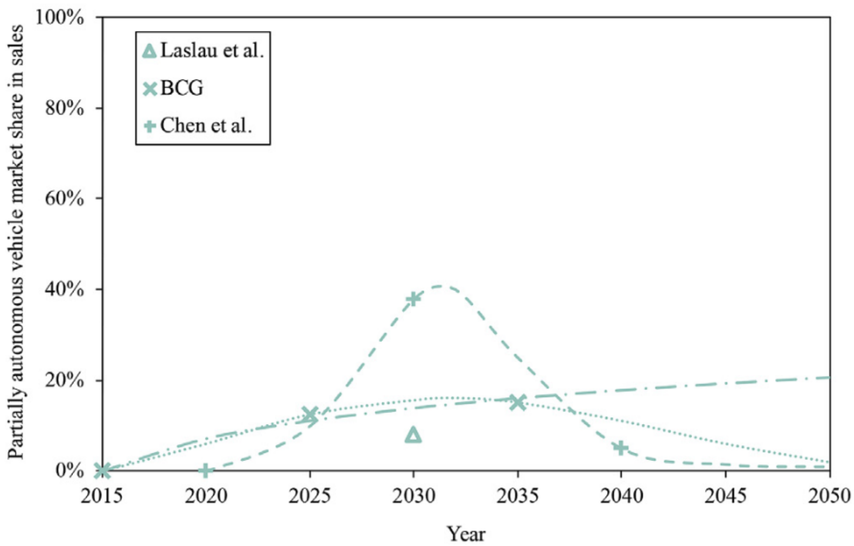

Figure 3.6 Predictions for *Partially autonomous* vehicle market share in sales [14].

To fully understand all the parts involved in the AD and LiDAR market it is important to acknowledge some concepts schematised in Figure 3.7, namely OEMs- Original Equipment Manufacturers - and Tier 1 - the ones who supply components directly to the original equipment manufacturer. Their importance will be explored later in this chapter.

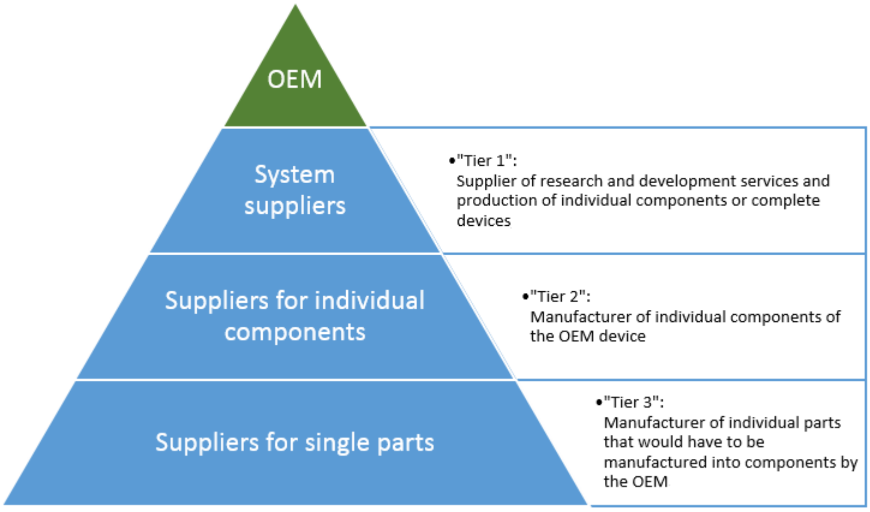

Figure 3.7 Generic Supply Chain [15].

Figure 3.8 presents the main companies involved in the AD market per sector. With this background out of the way, the focus falls into the LiDAR market. In the following pages, the leading LiDAR companies will be pointed out and briefly analysed in order to better understand the LiDAR State of Art.

Figure 3.8 Autonomous Driving Market. Adapted from [9].

In recent years, several LiDAR startups have been created and more than 85 companies are developing automotive LiDAR sensors using their unique approaches. Consumption of LiDARs are mainly dominated by Automotive sectors, especially the recent pool of investment in self-driving/autonomous cars. All the LIDAR companies are trumpeting the same message: better resolution, wider Field of View (FoV), longer range, more precision and, mainly, cheaper technology [16].

As the complexity and costs of new SW-driven functions, e.g., for AVs or connected cars, are huge, we see increased cooperation to share costs or speed up development. Even close competitors, such as BMW and Daimler or GM and Honda, are now working together, especially in the field of AD, to share the high development costs. Also, tier-1 suppliers and OEMs are intensifying their cooperation and are building strategic partnerships. For example, engineers from Daimler and Bosch are working together, located in two locations to develop HW and SW for AD [5].

Several top sellers are present in the automotive LiDAR sensors market. Some of them are: *Continental*, the well-known german automotive manufacturing company, specialised in brake systems and automotive safety; *LeddarTech* - a canadian company; Valeo - a multinational automotive supplier whose focus lies on the design, manufacture and sales of integrated systems components and modules for the automotive industry and, finally, the leader one, Velodyne - which provides a full line of sensors capable of delivering the most accurate 3D data in the market [3].

3.2.2 Function Principle

There are several distance measurement methods when using infrared sensors. Most common in automotive is "time-of-flight distance measurement." The time elapsed between transmitting and receiving of the light (laser) pulse is directly proportional between the measurement system and detected object. With "time-of-flight measurement," one or several light pulses are transmitted from the Laser source (Figure 3.9) and they are reflected by a possible existing object. The elapsed time until reflected signal is received is proportional to the distance. In Figure 3.9, the blue and red arrows represent the transmission and reception path of the laser beams, respectively.

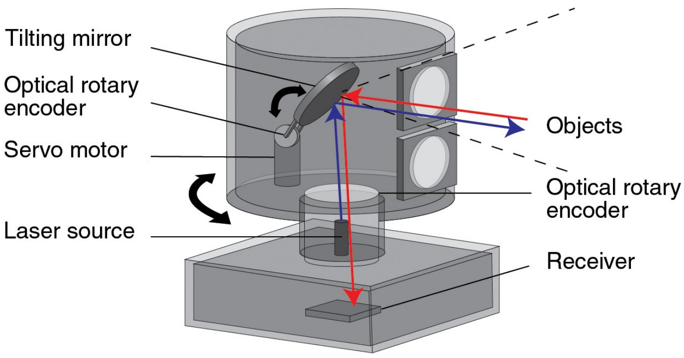

Figure 3.9 Diagram of the LiDAR optics and encoders - Type: Nodding mirror [17].

There are two established types of mirror system found in LiDAR scanning systems, either nodding or polygonal-mirror systems. Nodding (tilt) mirrors, the type which is the focus and will be better characterised further ahead in this dissertation, are the most common (scheme presented in Figure 3.9). Although both types use rotary encoders for closed-loop feedback control of the scan pattern, in the majority of the designs, the rotary encoder is mounted on the mirror shaft alongside an electromagnetic motor capable of tilting the mirror clockwise and counter-clockwise about the tilt axis. The nodding-mirror tilt axis is responsible for the vertical Field of View (FoV) of the instrument. Panoramic 360° data acquisition is the result of rotating the housing of the LiDAR system about the base. Manufacturers increasingly require that these systems rotate at a high rate of speed, in order to increase the resolution and accuracy of 3D images [13].

A reflected pulse of a fixed and single object (e.g., vehicle) has the shape of a Gaussian curve. Since the emitted light pulse travels twice the distance between the sensor and obstacle, the elapsed time between sending and receiving represents twice the distance to the object (consider Equation 3.1).

$$d = \frac{c_0 \cdot t}{2} \tag{3.1}$$

$$d = distance\, between\, the\, sensor\, and\, object$$
$$t = travel\, time$$
$$c_0 = speed\, of\, light (\approx 3 \times 10^8)$$

If there are several objects in the detection area of the sensor and therefore in the measurement channel, they can be recorded with an appropriate evaluation if the distance between the obstacles is sufficiently large enough. This is called multi-target capability of the system. If there is an increased attenuation of the atmosphere due to fog, rain, etc., then individual pulses are reflected on the water droplets in the air. Depending on the optical design of the system, this can lead to saturation behaviour in the receiver and the measurement could no longer possible [13].

This topic, specially the LiDAR optical system, has big relevance in this document and will be explored with more detail in Subsection 3.2.3.

3.2.3 Optical System

There are several different types of LiDAR systems, but they all operate on the same fundamental principles. A laser emitter produces an electromagnetic wave, which is launched from a source into the environment. Once this wave contacts an object it is reflected in some direction. Some of the reflected light returns to the device through a receiving lens and is registered by a photo-diode. This path is schemed in Figure 3.10. Meanwhile, a processor on-board keeps track of the amount of time that has passed since the laser was emitted. The total travel time for the light can then be used to calculate the distance travelled by the light [8] [13].

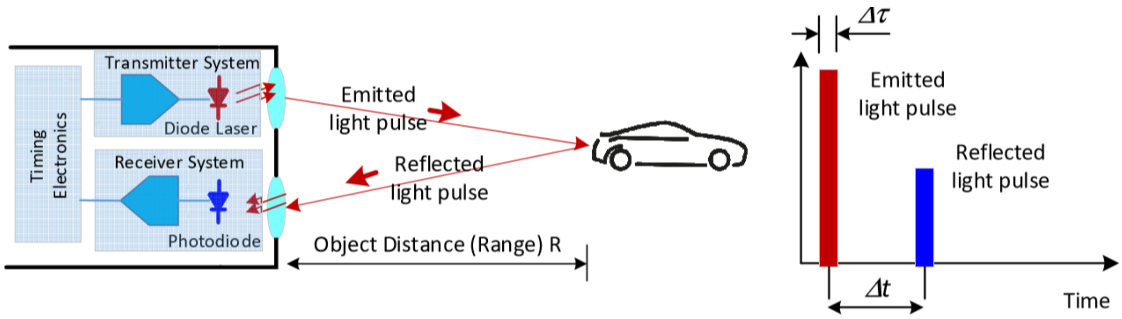

Figure 3.10 (a) Basic LiDAR operating principle; (b) Timing diagram of the pulses [8].

A scanning LiDAR system diffuses the laser into a thin vertical line (Vertical Field of View) - see Figure 3.11 - then sweeps it over the field of view (360º - Horizontal Field of View) to create a matrix of points from which the light was reflected back to the receiver. This allows the generation of 3 Dimensional cloud of discrete points which is relatively easy to process from a software perspective [18].

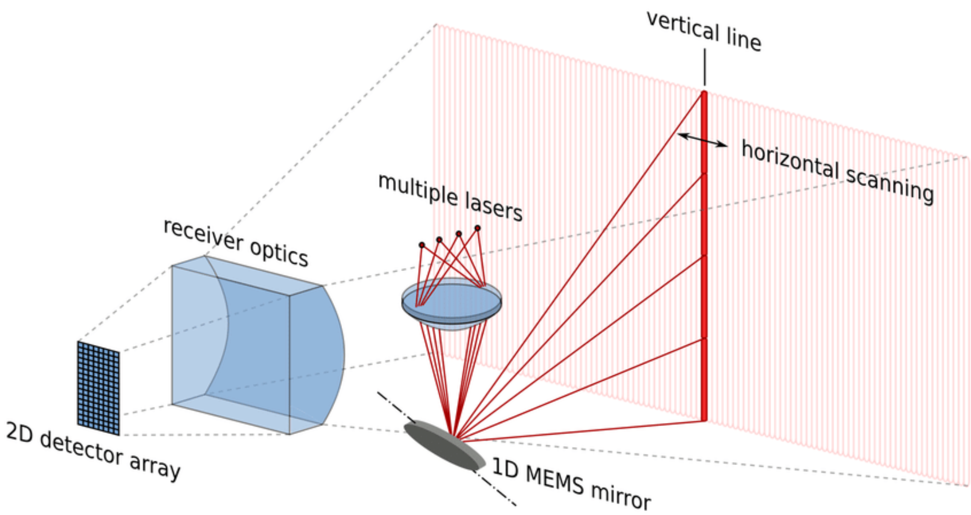

Figure 3.11 1D micro-scanning LiDAR - vertical laser beam line and scanning horizontally [18].

The operation of a time-of-flight LiDAR requires a pulsed laser capable of producing laser pulses a few nanoseconds long and with a high repetition rate. Wavelength, power, pulse length and repetition rate, as well as beam divergence are key parameters that impact the construction and performance of the LiDAR unit. Eventually, the selection of a given laser for a LiDAR unit is determined by the specific mode of LiDAR operation and by the performance, availability and cost of not only the laser itself, but also of the required photo detectors.

The three most common currently used or explored wavelengths for automotive LiDAR are 905 nm, 940 nm and 1550 nm, each with its own advantages and drawbacks. One consideration in LiDAR design is the presence of ambient light which can interfere with its operation. As such, an operating wavelength that corresponds to a local minimum in the solar spectrum at the surface of the Earth is preferable. The solar spectrum has such minimum around 905 nm, 940 nm and 1550 nm caused by absorption by water vapor in the upper atmosphere. Of course, the same absorption can have a detrimental effect on the round trip propagation of the LiDAR laser beam itself. Nonetheless, 905 nm has long been the standard wavelength for range-finding LiDAR.

The well-established and widely deployed *Velodyne* 360° spinning LiDAR has consolidated its position on the market significantly. Also, low cost high power edge emitting pulsed diode lasers at 905 nm are readily available from companies like *Lumentum, Hamamatsu, Osram* and many others, and so are the necessary photo detectors (silicon photo diodes or photo diode arrays), since 905 nm is within the range of detection by silicon, and thus also compatible with detector array technology.

One drawback of 905 nm lasers is that they fall within the range of wavelengths that can penetrate through the front and the interior vitreous humor of the eye, and reach the sensitive retina. Thus, safety rules limit the allowed power density that can be employed in LiDAR operation, and through that, they limit the 905 nm LiDAR range to within tens of meters to 100 m. The 1550 nm wavelength offers a significant advantage in this respect, as it falls beyond the 1400 nm retinal hazard limit. Light beyond 1400 nm gets absorbed in the front layers of the eye (cornea, aqueous humor and the lens) mainly because of watery absorption, and does not reach the retina. Power levels as much as 10 times or even 40 times higher than at 905 nm can be used. Also, the number of 1550 nm photons to be detected at any power level is 1.7 times larger than that of 905 nm photons at the same power, and less sunlight reaches the ground at 1550 nm compared to 905 nm. Because of all these, 1550 nm lidar can achieve longer range. *Luminar*, a LiDAR start-up company that has teamed up with Volvo, reports a range of more than 200m at only 10% target reflectivity for its macroscopic-mirror mechanical scanning 1550 nm lidar. The use of the 1550 nm laser diodes as well as other components for fiber optics communications networks is also an advantage exploited in the development of coherent Frequency Modulated Continuous Wave (FMCW) LiDAR. The downside of a 1550 nm LiDAR is the increased cost of the detector, as well as the lack of detector array offerings (for flash LiDAR), since more exotic materials like Ge, InGaAs, or InGaAsP detectors have to be used. The use of optimized detectors is paramount to the LiDAR performance, and another way to improve the range of a LiDAR unit. Because only a small fraction of the photons emitted by the laser make it back to the detector, selecting the right photo detectors with high detection sensitivity, high internal gain and low noise is critical. For 905 nm LiDAR, silicon avalanche photo diodes (APDs), single-photon avalanche diodes and silicon photo-multipliers (SiPMs) are popular detectors, each with its specific advantages and limitations. For 1550 nm lasers, mostly InGaAs photo-diodes or avalanche photo-diodes are used [8].

3.2.4 Propagation of light in LiDAR operation

Three fundamental optics phenomena bear heavily on the performance of a lidar system: **absorption, scattering and reflection of light**. In contrast to radar, LiDAR has only limited performance in poor weather conditions (rain, snow, heavy fog). This is due mainly to absorption of light by water and to atmospheric scattering of light out of the directional laser beam, thus reducing the photon flux available for reflection by the target and eventually for detection by the LiDAR unit. The reflection of light, on the other hand, is what allows the LiDAR to detect the environment around it. The reflections used for constructing the 3D point cloud images are obviously mostly the diffuse reflections from the various points of the target scene, but both diffuse and specular reflections contribute and affect the performance of the system.

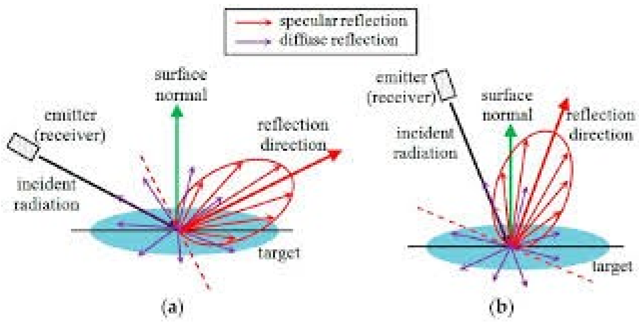

Figure 3.12 (a) Diffuse and specular reflection by a surface. At large incidence angles, only diffuse reflections reaches the receiver of the LIDAR unit ; (b) at smaller incidence angles, both diffuse and specular reflection reach the receiver [19] [20].

In the real case of protective optical window, when a laser beam hits the surface, the physical phenomena that can occur are: reflection, transmission, light scattering and absorption. Theoretically, it is possible that only one of them occurs, however, that his highly unlikely and most probably all four phenomena occur in different amounts, which must be known to understand their influence on the optical properties of the material. The transmission is usually easy to measure and it is a what we really need to know.

Maximum transmission at the near-infrared (NIR) area of interest (around 1550 nm) is a requirement in our case.

The optical performance of a certain material results from its interaction with electromagnetic radiation. So, if the interaction of electromagnetic waves around 1550 nm with the possible substrate material/coatings is minimum, it means that substrate will have high potential for being used as Protective Optical Window for a LiDAR system.

Optical properties studies, usually gives special emphasis to the visible part of the electromagnetic spectrum, Figure 3.13.

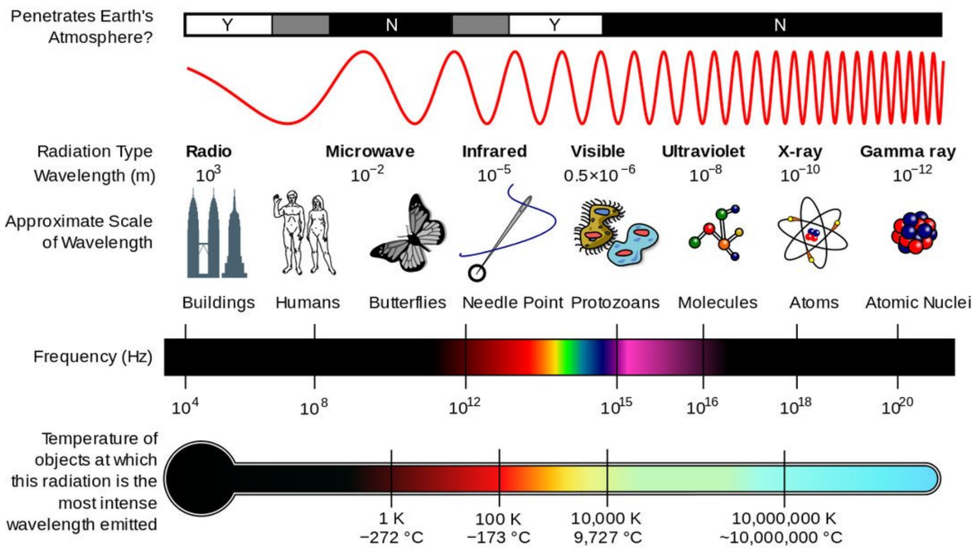

Figure 3.13 Light Spectrum [19].

However, in case of the present study, the most important part of the spectrum is NIR radiation, which is between 700nm and 2500 nm.

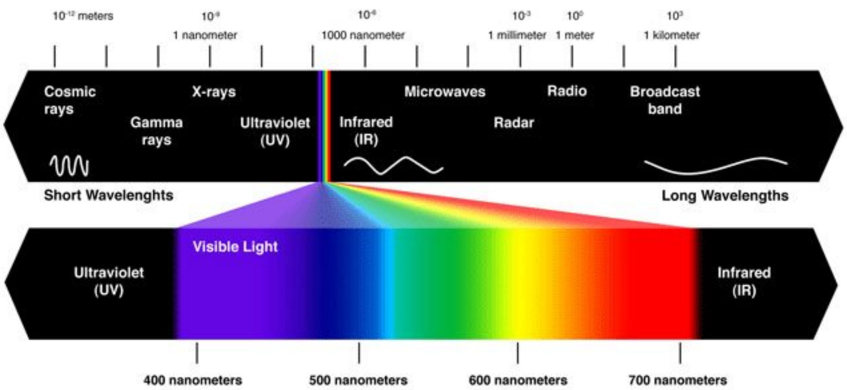

Figure 3.14 Visible Light Spectrum [19].

The solar spectrum, Figure 3.14, consists of Ultraviolet light (300-400 nm), visible light (400-700 nm) and near-infrared light (700-2500 nm). Some of the manifestations of electromagnetic radiation are interpreted by the wave theory of the light. Light is part of the electromagnetic spectrum and is visualised as a wavelength, λ , to which are associated a magnetic field and an electric field.

The electromagnetic wave can be described as the ratio between the electric field E_m and magnetic field B_m, given by Equation 3.2 [20].

$$\frac{E_m}{B_m} = c \tag{3.2}$$

Where c represents the speed of light.

The energy of the radiation E is related to the wavelength λ and to the frequency v, according to Equation 3.3 [20].

$$E = hv = \frac{hc}{\lambda} \tag{3.3}$$

Where h is the Plank constant, c the speed of light in vacuum, and hc the photon energy according to the corpuscular theory [20].

The interaction of light with transparent materials takes place in several ways, as can be seen from Figure 3.15.

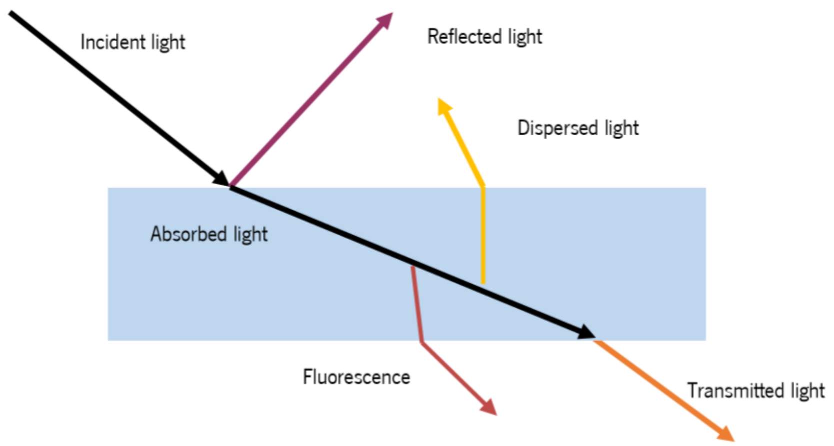

Figure 3.15 Interaction of light with a transparent material [19] [8].

When light strikes a surface, phenomena such as reflection, dispersion and/or absorption might occur. Besides that, the light can also cross the material. In some cases, fluorescence phenomena can also occur. Disregarding possible fluorescence phenomena, the interaction of light with the medium (transparent material) can be described as:

Incident Light intensity (I_0) = Reflected quantity (R) + Dispersed quantity (D) + Absorbed quantity (A) + Transmitted quantity (T).

This can generally be represented by Equation 3.4, where "1" represents the total amount of light striking the surface.

$$1 = R + D + A + T \tag{3.4}$$

In materials with good optical quality the phenomena of dispersion and absorption can be disregarded, which means that:

$$1 = R + T \tag{3.5}$$

3.2.4.1 Reflection

When the light reaches a surface and the surface is smooth without roughness, the light is reflected specularly, which means that it obeys the laws of reflection. According to these laws, a fraction of incident light is reflected by the surface with an angle equal to the angle of incidence, where the incident ray, reflected ray and the surface normal at the point of incidence are in the same plane [21], Figure 3.16.

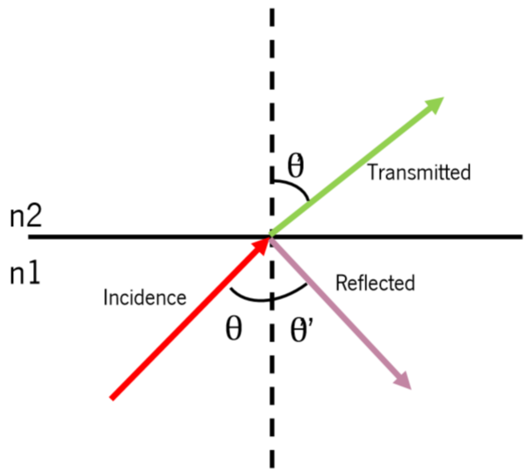

Figure 3.16 Reflection Law $\theta = \theta'$ [8] [19] .

Specular reflection is the only form of reflection that obeys the laws of reflection. The fraction of light that is reflected specularly by a surface is related to the index of refraction of the material by the *Fresnel* equation [20]:

$$R \approx (\frac{n_2 - n_1}{n_2 + n_1})^2 \tag{3.6}$$

Where **R** is the reflected light fraction and n_1 and n_2 are the refractive indices of material 1 and 2, respectively.

When light is transmitted from the air to the interior of a transparent material, the Fresnel law can be described through the same previous equation [20]:

Thus, it is possible to conclude that the higher the refractive index of a solid, the greater it is the specular reflection.

If we take as an example the real case of the protective optical window and consider that it is made of polycarbonate, the loss of light by specular reflection, with a refractive index of n=1,58 and, the air's equal to approximately 1, is according to Equation 3.6 [20].

$$(\frac{1.58 - 1}{1.58 + 1})^2 \approx 0.05 \tag{3.7}$$

This means that whenever a beam of light passes through the protective optical window/air interface, its intensity is reduced by 5%. This means that after reflection on the first interface (air/protective optical window), the luminous intensity is reduced to 95%. After crossing the second interface the luminous intensity is again reduced by 5%, which means that the total amount of transmitted light is 90%.

On the other hand, when the light reaches a rough surface, the reflection is not only specular but it has also a diffuse component as shown by Figure 3.17.

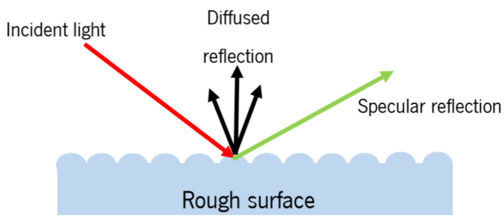

Figure 3.17 Diffuse and Specular reflections occurring on a rough surface [19].

It is the *diffused reflection* component which allows us to see objects when illuminated, their texture and colour, and allows us to distinguish them from the environment. The reflection component (R) is given by the sum of diffuse reflection ($R_{diffuse}$) with specular reflection ($R_{specular}$) - Equation 3.8 [20].

$$R = R_{diffuse} + R_{specular} \tag{3.8}$$

Mixed reflection is the combination of specular reflection and diffuse reflection, and it is the base of objects reflection.

3.2.4.2 Refraction

When light passes through two transparent mediums/materials with different densities, such as air and a polymer for instance, the direction of light beam is changed and its speed and wavelength vary abruptly at the interface. This phenomenon is called *refraction of light* [21].

A simple way to describe the index of refraction of a certain medium/material is through the calculation of the ratio of the velocity of the speed of light in vacuum ($c \approx 3 \times 10^8$) by the speed of light of the atmosphere, v (m/s) - see Equation 3.9 [20].

$$n = \frac{c}{v} \tag{3.9}$$

When a beam of light passes from medium 1 to medium 2 (interface) with different index of refraction n_1 and n_2, the angle of incident beam θ_1 (incident angle) and the angle of transmitted beam θ_2 (refractive angle), measured with respect to normal, satisfy the relation described by Snell's Law [20]:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{3.10}$$

Whenever the light passes from one atmosphere to another optically denser, its trajectory undergoes a deviation, approaching the normal incidence. If, on the other hand, the light passes from an atmosphere of higher refractive index to a lower one, its path also undergoes a deviation but this time moving away from the normal. In this case there is an angle of critical incidence (limit angle above which total internal reflection of light occurs) [21] - see Figure 3.18.

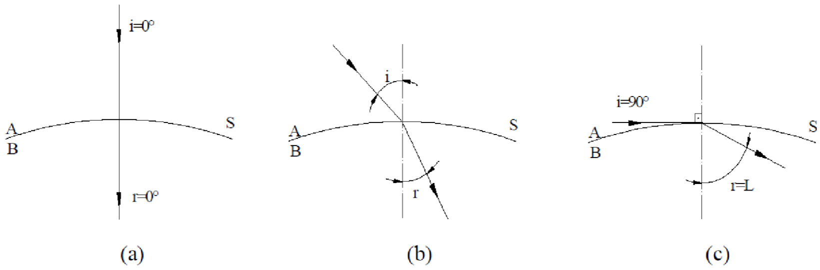

Figure 3.18 Limit angle above which total internal reflection of light occurs [21].

The value of this limiting angle, r, depends on the refractive index of the atmosphere, according to Equation 3.11 [20].

$$\sin r = \frac{1}{n} \tag{3.11}$$

Knowing that the most suitable materials for the protective optical window have an index of refraction between 1.49 and 1.59, the value of the critical angle will be between 42° and 39° in relation to the normal at the point of incidence, respectively .

$$r = \arcsin \tfrac{1}{1.49} = 42°$$
$$r = \arcsin \tfrac{1}{1.59} = 39°$$

3.2.4.3 Light scattering and absorption

When light crosses a material, and thereby changes its direction, the phenomenon that happens is designated by *Light scattering* and is caused by optical non homogeneities on the material. This phenomenon is a measure of how much the index of refraction of a material changes with respect to wavelength and also determines the separation of wavelengths known as chromatic aberration. The chromatic aberration is responsible for the rainbow effect that we can see in optical lenses, prisms, and similar optical components (Figure 3.19). The different colours observed in the rainbow of a prism correspond to different frequencies of electromagnetic spectrum, caused by the deviation of the light beam between the air/material and material/air interfaces. Light scattering can be highly desirable phenomenon in the case of an equilateral prism but in other applications, this phenomenon can be detrimental to a system's performance [21].

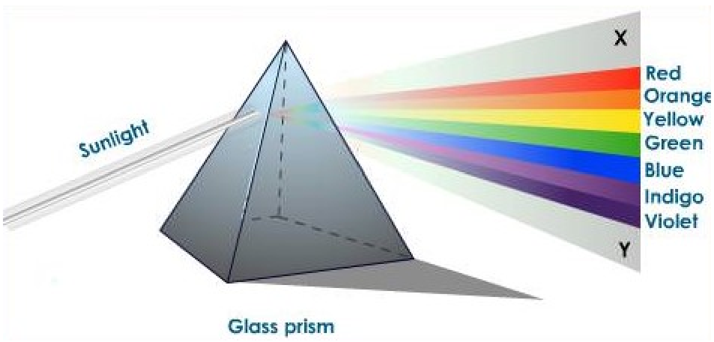

Figure 3.19 Dispersion of Light [20].

If, on the other hand, the light "disappears" by the encounter with the material we call it the absorption phenomenon. Both types of phenomena, scattering and absorption, will cause a light beam attenuation when passing through the material and, in both cases, the transmitted intensity will decrease exponentially with the thickness increase (x) of the material. If the attenuation is due to absorption, the transmitted intensity I is usually written by Equation 3.12 [20].

$$I = I_0 \times 10^{-\alpha x} \tag{3.12}$$

Where **I** is the light intensity, emitted at the output, and I_0 is the incidence intensity, x is the thickness of the material and α is the absorption coefficient.

The major part of the scattered light originates at surface irregularities and other imperfections, such as scratches. Bennet and Porteus (1961) investigated the effect of surface roughness on the reflectance and found a functional relationship between the total amount of light scattered by a surface and a surface roughness, Equation 3.13 [20].

$$TIS - 1 - \frac{r_s}{r_0} = \exp -(\frac{4n\sigma \times \cos i}{\lambda})^2 \tag{3.13}$$

Where TIS is the total integrated scattering, r_s and r_0 are specular reflectance of the rough and perfectly smooth surface, respectively. i is the angle of incidence light, σ is the mean surface roughness in mm and λ is the light wavelength, also in mm.

3.3 LiDAR | Advantages and drawbacks

LiDARs are complex electronic systems, having by consequence technological but also theoretical limitations.

Up to the present moment, level 2 systems have been designed around two technologies: radar and camera. Automakers can improve the effectiveness and efficiency of driver assistance features with the implementation of a system in which LiDAR is a key component for perception. For example: if there is bright sunlight or if it is really dark at night, some of the camera-based features are not reliable and not available all the time [22]. LiDAR is inherently superior to camera and radar in certain crucial performance aspects, such like:

- **Surface data has a higher sample density** - LiDAR gives a much higher surface density as compared to other methods of data collection. This improves results for some kinds of applications such as flood plain delineation. The result of the flood-plain delineation will be a new dataset of water surface elevations and/or inundation depths;

- **Capable of collecting elevation data in a dense forest** - LiDAR technology is capable of collecting elevation data from a densely populated forest thanks to the high penetrative abilities. This means it can map even the densely forested areas;

- **Can be used during day and night** - LiDAR technology can be used day and night thanks to the active illumination sensor. It is not affected by light variations such as darkness and light. This improves its efficiency;

- **Does not have any geometry distortions** - LiDAR sensors are not affected by any geometrical distortions such as angular landscapes unlike other forms of data collection;

- **It can be integrated with other data sources** - LiDAR technology is a versatile technology that can be integrated with other data sources which makes it easier to analyse complex data automatically;

- **It has minimum human dependence** - LiDAR technology, unlike photogrammetry and surveying has minimum human dependence since most of the processes are automated. This also ensures valuable time is saved especially during the data collection and data analysis phase [13].

However, besides all of those previous advantages for autonomous driving, specially the capability to generate precise three-dimensional images of everything from cars to trees to cyclists in a variety of environments and under a variety of lighting conditions, its major disadvantage is the current cost, as seen in Figure 3.20, which presents the approximated cost of each ADAS feature in the car, being the LiDAR one of the most expensive features [9].

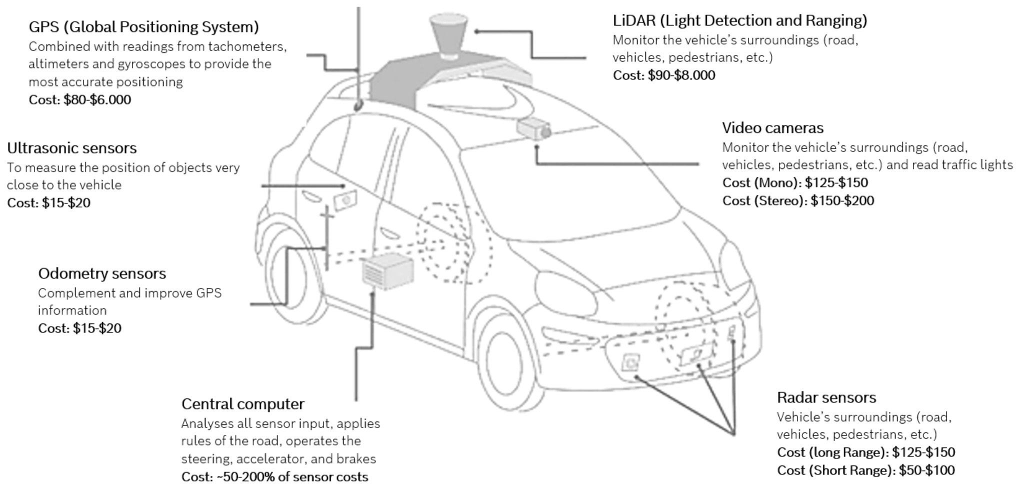

Figure 3.20 Cost of several Elements in Autonomous Driving [9].

In the end of the day, for autonomous vehicles, a combination of LiDAR with camera based systems ensures the largest potential in terms of object and environment recognition. The only thing not possible to recognise is information on surfaces, namely written letters on a traffic sign. The trend for self-driving cars goes into the direction of sensor fusion which combines camera based technologies with radar or laser sensors, so that each technology is able to play its advantages in a highly integrated system [23].

3.4 System Requirements

ISO (the International Organisation for Standardisation) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organisations, governmental and non-governmental, in liaison with ISO, also take part in the work. This requirement specification collects the top level LiDAR mechanics and optics architectural requirements (functional and non-functional) in order to fully oblige to these International Standards.

Project development demands a previous definition of the requirements, after the concept idealisation. The mechanical, optical, functioning and manufacturing requirements which will lead to an automotive Protective Optical Window and passive and active solutions must be defined.

The overall goal is that the POW should be always clean during operation, for an always correct and accurate change of information between the device and the vehicle surroundings. It is essential, then, to specify what is considered a clean or dirty surface, which will be later explored in this dissertation, in Chapter 5. The material requirements, manufacturing requirements and functioning requirements for both systems are established hereinafter.

Material Requirements

Regarding materials the requirements are as follows:

- **Thermal requirements**: all the materials considered to produce the POW and the active cleaning system must withstand temperatures between -40°C up to 85 °C, without deformations that could affect the self-cleaning ability or its integration with the active cleaning system. This range of temperatures are the ones expected for the LiDAR device to withstand and are part of Automotive Standards;

- **Optical requirements**: the material for the POW should have an optical transmittance above 85%, and a Haze value below 2%. These values should stand valid for the NIR wavelengths commonly used on LiDAR devices, typically lying above 800 nm and bellow 1600 nm. All materials should also be UV resistant to avoid a fast degradation of material properties due to unavoidable sun exposure;

- **Mechanical requirements**: the chosen materials should present similar values of scratch, wear and impact resistance as the ones commonly presented by materials used on the most recent automotive headlamps. If there is the need for coating the materials, these properties should not be significantly affected. With or without coatings, chemical resistance to cleaning and environmental agents must also be ensured.

Functioning Requirements

It is expected to assemble both systems, the POW and the active cleaning system, on a functional prototype. Thus, they should work perfectly together without compromising any of the requirements mentioned above. Passive and active cleaning systems should be tested separately and together to find a commitment between them, that leads to an effective cleaning solution.

3.5 Regulatory Framework

Automotive industry has some regulations that covers every device installed in a vehicle. Regarding the standard for automotive cleaning equipments, it is within the scope of UNECE Regulation No. 43 that refers to uniform provisions concerning the approval of safety glazing materials and their installation on vehicles. This regulation applies to:

- Safety glazing materials intended for installation as windscreens or other panes, or as partitioning, on vehicles of category L with bodywork, M, N, O, and T;
- Vehicles of categories M, N and O with regard to the installation of these materials (ategory M: vehicles carrying passengers. Category N: vehicles carrying goods. Category O: trailers);

It designates some general requirements for glazing materials. Like, for instance, all glazing materials, including those for the manufacture of windscreens, shall be such that, in the event of shattering, the danger of bodily injury is reduced as far as possible. The glazing material shall be sufficiently resistant to incidents which may occur in normal traffic, and to atmospheric and temperature conditions, chemical action, combustion and abrasion. Also, safety glazing materials shall be sufficiently transparent, shall not cause any noticeable distortions of objects as seen through the windscreen, and shall not give rise to any confusion between the colours used in road traffic signs and signals. In the event of the windscreen's shattering, the driver should be able to see the road clearly enough to be able to brake and stop the vehicle safely [24].

This norm also prescribes some listed tests that safety glazing materials shall be subjected, such as mechanical, environmental resistance and optical tests. Regarding the optical tests, this regulation refers the light-transmission test with the purpose to determine whether the regular transmittance of safety glazing exceeds a specified value. In the case of a windscreen, the regular light transmittance shall not be less than 70% [24].

3.5.1 Problems & Challenges

Stigmas around fatal autonomous vehicle crashes are not the biggest challenge for the rising automotive LiDAR industry. LiDAR sensors might face some challenges that have to be taken into account like:

- **Elevated Cost** - LiDAR technology must have a viable price in order to be applicable on the market;
- **Range and Perception** - Variations and limitations that might affect the capability of the vehicle to "see" without flaws;
- **Robustness** - All the parameters like vibration, shock, wear and tear, cleaning must be taken into consideration;
- **Safety and Edge Cases** - Potentially flaws need to be corrected regarding weather conditions and traffic situations[25].;

At the center of all LiDAR systems is a laser. The laser determines the overall system performance and its characteristics such as the beam divergence and laser beam quality. Other characteristics, such as the pulse duration and timing jitter determine longitudinal accuracy. Pulse energy determines range. So, for a long range sensor, having high definition will require a high power laser with a short pulse and good timing jitter. It should be noted that one of the main challenges for greater application of LiDAR is that many common lasers do not provide the wavelength coverage desired or power and energy levels that are useful. Increasing the power level to extend the range could easily lead to an excessively high power density that would exceed the limit for Class 1 laser safety [1]. In such cases, the laser becomes an ocular hazard and the laser beam must be expanded to reduce the power density to an acceptable limit. LiDAR systems for autonomous vehicles operate in the near IR, away from the visible spectrum of the human eye. Current systems employ sources operating at a wavelength of 905nm, the peak responsivity of silicon detectors. Recently, due to concern for laser safety, more systems are transitioning towards 1550nm and employ InGaAs detectors.

All of this parameters can affect LiDAR sensors performance on the road (highway or not). Current optical lasers cover a much wider wavelength range, even though with lower output power and limited scanning coverage within a short time period. In addition, there are several continuous wave lasers that emit in the 3000–5000nm wavelength range,

[1]Class 1 - Level in which there is no risk for the eye or possible vision complications.
Class 1M - Safe for all conditions of use except when passed through magnifying optics such as microscopes and telescopes.
Class 2 - Safe because of the blink reflex if not viewed through optical instruments. Class 3R - It is considered safe if handled carefully, with restricted beam viewing.
Class 3B - It is hazardous if the eye is exposed directly, but diffuse reflections such as those from paper or other matte surfaces are not harmful.
Class 4 - It can burn the skin, or cause devastating and permanent eye damage as a result of direct, diffuse or indirect beam viewing.

but often have to be cooled or changed in semiconductor composition to achieve wide wavelength tuning. [26] [25].

In this work, the most critical concern falls upon how "clean" must the protective optical window - the optical interface between the optical components and the environment - be to ensure the perfect and demanded performance of the LiDAR sensor, Section 3.6. Therefore, to introduce the following Chapter it is important to highlight the challenges that LiDARs might face on this matter. These difficulties will be introduced in Chapter 5.

3.6 Protective Optical Window

The POW will be one of the components of the Bosch´S LiDAR sensor, illustrated in Figure 3.21. It will ensure the protection of the internal components from several potential pollutant materials, that might stick to it, including, for example: dust, mud and insects.

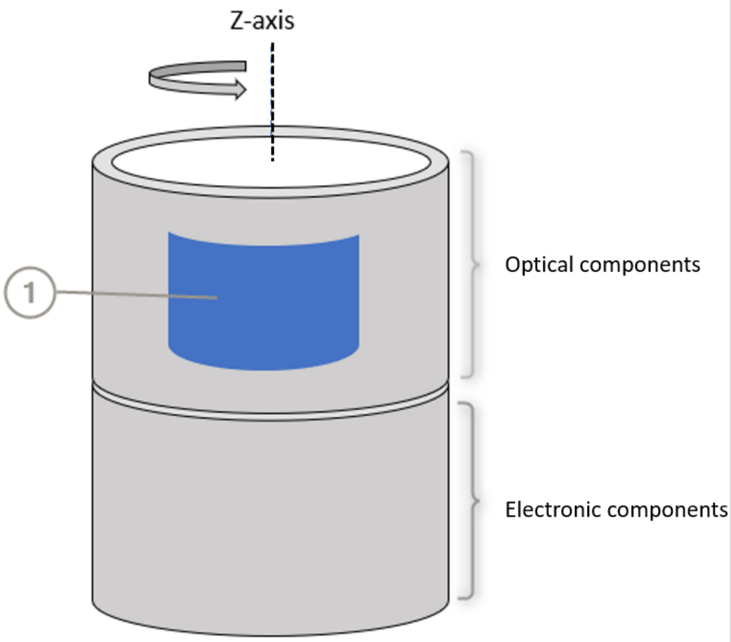

Figure 3.21 POW representation in Bosch's LiDAR concept (1) Protective Optical Window (POW).

The POW must present an acceptable transmittance, a good emission and reception of all the laser signals emitted and consequently reflected and received, without creating optical irregularities when those signals cross the interface itself. Used as an entrance window, the POW must provide high light transmission while remaining strong, lightweight, and resistant to potential corrosive environments or thermal changes. High transmission at the relevant laser wavelength is especially important as it ensures that light passes unimpeded through the entrance window, which serves as a protective cover for the components inside. If the entrance window impairs the LiDAR signal, it will not see its surroundings accurately.

Since different kinds of pollution can affect the sending and receiving laser signals, it is necessary to project a cleaning system for the POW outer surface, in order that small particles, insects and other pollutants do not stick or can be easily and effectively be cleaned in order to do not affect the global performance of the system.

This protective window should be integrated in the housing structure and should be made of a material with maximum transparency at the correspondent wavelength λ, good UV resistance, good mechanical behaviour, chemical resistance, good scratch resistance and self-cleaning features [27] [28] [29].

Firstly, it is important to evaluate the products and materials that already exist, taking into account their characteristics and possible competitors, to understand the best design approach of the POW, which will be presented in the next Section of this dissertation, 3.6.1. After that it is necessary to build a design not only based on the findings coming from the market analysis, but also with respect to the specifications required, the scenarios to which Bosch´s LiDAR system might be exposed to and the physical light phenomena that occur when the laser beam crosses the POW. All in order to structure and identify materials that can be used in it.

In Figure 3.22 it is schematised the transmission of light from the inside (laser source) to the outside, and, once reflected, the reverse path from the outside to the inside, while crossing the POW. The yellow and orange arrows represent the transmitted (Tx) and received (Rx) beams, respectively.

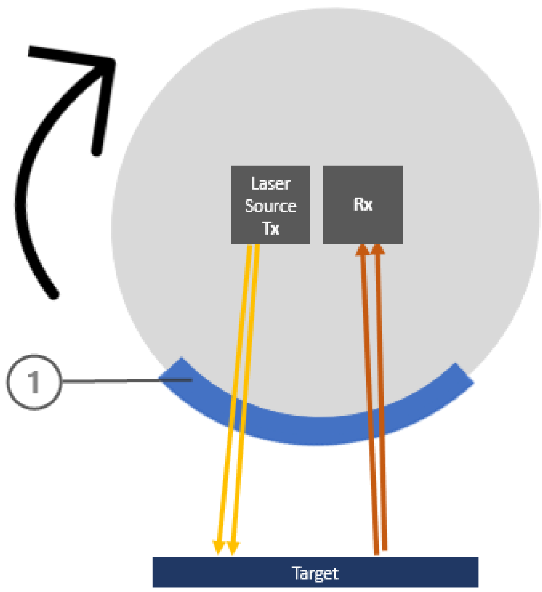

Figure 3.22 Schematic diagram of glass cover window [28].

3.6.1 Optical materials and properties

Optical materials are used to produce optical devices and systems. The materials used for this type of application are glass and polymeric materials. Selecting the most suitable material for a certain optical specification requires an evaluation of the environment in which it is anticipated that they operate and their required performance. The most successful choice passes by selecting a material with physical properties compatible with the intended applications and having optical properties consistent with the required level of performance. The most important physical properties to consider are density, hardness, stiffness, service temperature, electrical and thermal conductivity and radiation resistance [30].

Optical properties worthy of consideration are spectral transmission, refractive index (and its variation with temperature), purity, homogeneity, surface finish and strain [31].

Density determines the weight of the component. Plastics, for optics, vary in density from $0.83g/cm^3$ to $1.4g/cm^3$. This may be contrasted to optical glasses ranging from $2.3g/cm^3$ to 6.3 g/cm^3. The number of elements required in an optical design may often be reduced by the use of aspheric surfaces, easily achieved with plastics, and such consideration should be crucial in weight critical applications.

A drawback of plastic compared to glass is its relative softness, making it susceptible to surface damage (scratches, digs, etc.). The hardness of plastic optics is difficult to quantify (compared to glass) since it is dependent of not only the material, but also of the processing. The compressibility of thermoplastic polymers normaly limits the success in the use of harder surface coatings to protect against superficial abrasion. The rigidity of a polymer determines its impact or shatter resistance and is therefore a factor that impacts safety. Evaluation of rigidity is based on examination of the plastic's elastic modulus (Young's Modulus) and the elongation factor at yield. Since these properties are dependent on not only the specified polymer alloy and additives, but also on the processing history of the polymer, it is often difficult to precisely determine end product rigidity. In selecting a plastic for a desired degree of rigidity, consideration must also be given to the fact that properties which contribute to impact resistance may be liabilities if the optical part is subjected to some torsion or compressive stress.

Service temperature limits for plastic optics (60 °C to 250 °C) are substantially less than for optical glasses (400 °C to 700 °C). Furthermore, their thermal conductivity may be as much as an order of magnitude less than that of glasses and their thermal expansion coefficient may be as much as an order of magnitude higher than glasses. Therefore, applications, in which thermal transients may be encountered, require consideration of thermal gradients to assess if performance requirements can be maintained in the environment of application. The thermal expansion of plastic is higher than glass's. For instance, the linear thermal expansion of acrylic is $7x10^5$/°C, while for common crown glass is $0.7x10^5$/°C.

Usually, optical plastics are unfilled polymers and, also, effective electrical insulators.

They are, therefore, susceptible to build up electrical charge on their surface and, therefore, enable the attraction of charged contaminants. Whenever these contaminants are harder than the plastic surface. what may occur is superficial damage, when attempting to clean the surface [30] [32], the main topic of this dissertation.

An inherent property of optical plastics is its hygroscopicity, the phenomenon of attracting and holding water molecules via either absorption or adsorption from the surrounding environment. A typical plastic optical surface may absorb from 0.003% to about 2% water by weight, producing dimensional changes and minor alterations in spectral transmission. Surfaces may be coated with less hygroscopic materials to reduce water absorption.

Optical plastics are susceptible to radiation. Intense ultra-violet and ionizing radiation will induce polymer chain cross-linking, the degree of which depends on the particular polymer chemistry. Optical plastics also have a tendency to fluoresce under sufficiently intense high-energy radiation, a phenomenon that could degrade their utility in certain applications.

Optical plastics are inherently limited to visible light applications. Most optical plastics begin to absorb in the blue portion of the visible spectrum and have absorption bands at about 900nm, 1150nm, 1350nm, and become totally opaque at about 2100 nm. The similarity in the absorption spectra of most optical plastics can be attributed to the similarity in their molecular structures. A few plastic materials, if made sufficiently thin, have been used in IR filter applications due to a narrow band of transmission leakage in the far infrared. In general, optical plastics have lower refractive indices than optical glasses. When designing a lens, it is desirable to use a high refractive index from the standpoint that the optical power required to form an image is a combination of the refractive index and the curvature of the optical surface. Commonly, these two variables are traded off in the lens design process. However, curvature contributes more to aberration than refractive index and it is thus desirable to achieve optical power from a low curvature high refractive index material leaving plastics at a disadvantage. The variation of refractive index with temperature, can range from 6 to 50 times greater than that of glass depending on the specific materials being compared [30] [32].

Some of the more important optical and thermal properties of thermoplastics and thermosets are listed in Table 3.1.

Table 3.1 Optical and thermal properties of Optical materials [30]. [32]

	Units	**Acrylic** PMMA (Lucite) (Plexiglass)	**Styrene** Polysytrene (Dylene) (Styron) (Lustrex)	**NAS** Methyl Methacrylate Styrene Copolymer	**SAN** Styrene Acrylonitrile (Lustran) (Tyril)	**Poly-carbonate** (Lexan) (Merion)	**TPX** Methylpentene (TPX)	**ABS**	**ADC** Allyl Diglycol Carbonate (CR39)	**Glass** BK 7
Refractive index, n										
n_d (589.3)		1.491	1.590	1.533-1.567	1.567-1.571	1.586	1.467	1.538	1.504	1.517
n_c (656.3nm)		1.488	1.585	1.558	1.563	1.581	1.464		1.501	1.514
n_f (486.1nm)		1.496	1.604	1.575	1.578	1.598	1.473		1.510	1.522
Abbe Value, V_d		61.4	31.1	35	37.8	34.5	51.9		56.0	64.6
Rate of Change in index with Temperature	dn/df x 10^{-5}/°C	-8.5	-12.0	-14.0		-11.8 to -14.3			-14.3	+0.3
Coefficient of Linear Expansion	10^{-5}/°C	6.74@70°C	6.0-8.0		6.5-6.7	6.6-7.0		0.83	11.4 25 to 75°C 14.4 75 to 125°C	0.71
Deflection Temperature										
3.6°F/min. 264 psi	°C	92	82		99-104	142		90		
3.6°F/min. 66 psi	°C	101	110		100	146		84		
Recommended Max. Cont. Service Temp.	°C	92	82	93	79-88	124			100	
Thermal Conductivity	cal/sec-cm°C x 10^{-4}	4.96	2.4-3.3	4.5	2.9	4.65	4.0		5	0.266
Haze	%	2	3	3	3	3	5	12	3	
Luminous Transmittance	%, Thickness 3.175mm	92	88	90	88	89	90	79-90.6*	93	99.9
Water Absorption	%, Immersed 24 hr @ 23°C	0.3	0.2	0.15	0.2-0.35	0.15			0.2	
Mold Shrinkage	%	0.2-0.6	0.2-0.6	0.2	0.2-0.6	0.5-0.7	1.5-3.0			

*Luminous Transmittance 79%, thickness 6.35mm, 90.6%, thickness 0.381mm

Analysing Table 3.1 is perceivable that, besides glass, the materials with a higher value of transmittance are Acrylic, TPX, NAS and Polycarbonate. Thus, it is essencial to gain a greater understanding about them.

Acrylic is a moldable material, has good stability and is easy to machine and polish. Being it an hygroscopic material, the machining operation affects its optical properties, because since its low thermal conductivity reduces heat dissipation, a lubricant such as water must be applied when it is machined, and then, water is absorbed. The luminous transmission of acrylic is about 92%.

Polycarbonate, exhibiting high impact strength, has found application as street light lenses, construction-warning lights, automobile tail lights and other applications which require high durability. Ultraviolet degradation from sunlight has been inhibited by use of stabilizers with only 5% loss in transmission. Polycarbonate performs well over a broad range of temperature (-137 °C to 121 °C) , thus within the automotive range. It has a tolerable coefficient of thermal expansion, heating to 104 °C resulting in an increase in linear dimensions of only 0.07%.

PXMethylpentene (TPX) is a light weight plastic with excellent electrical properties. It is unaffected by many chemicals at temperatures up to 160 °C. Its major disadvantage is that it shrinks from 0.15 to 0.30 cm/cm during molding.

Copolymers, formulated from mixtures of styrene and other polymers, provide diversification of optical properties. NAS is a blend of 70% acrylic and 30% styrene.

3.6.1.1 Coatings

Different types of coatings may be applied in order to optimise the optical characteristics, such as: reflective coatings, anti reflection coatings, anti abrasion coatings and anti static coatings.

Reflective Coatings

Reflective coatings are commonly metal coatings, aluminium or chromium. A dielectric protective coating can be applied over the metal coating to enhance durability and reduce oxidation.

Anti reflection Coatings

Knowing that optical polymers exhibit specular properties similar to glass's, optical coatings are often necessary in polymeric optical systems. The coatings deposited upon polymer substrates fall mostly into four categories: coatings to improve reflectivity, to suppress specular reflection, to improve abrasion resistance and to retard accumulation of electrostatic charge. Losses in transmission occur in transparent materials due to surface reflections at the air/material interface.

Anti abrasion Coatings

Both inorganic materials and organic materials are used to reduce susceptibility to scratching. Inorganic materials used for anti reflection may be applied in thicker films to provide a more scratch resistant surface. The ultimate thickness is limited by internal stress and the internal expansion between the coating and the substrate. The utility of the coating can be compromised by external pressure collapsing the underlying substrate and fracturing the coating. To allow a better understanding, an hard coating is basically a varnish, usually applied by dipping, that uniformly covers all surfaces and brings an improved scratch resistance.

Anti static Coatings

A wise choice of materials used for anti reflection and/or anti abrasion coatings may provide sufficient conductivity to achieve reduced accumulation and dissipation of static charge.

The samples, to be tested after, are requested from suppliers and have different properties, coatings (anti-reflex, Anti-Finger-Print and hard coatings) and pigments (transmission of light in the NIR region). The results for each chosen material, based in all the theoretical information gathered previously in this chapter, are presented in Chapter 7. The POW material will be selected in conformity with those results.

3.7 Bosch's LiDAR

After understanding all the State of Art regarding LiDAR and its associated technologies, it is important to define Bosch's strategy for the development of the prototype in which this dissertation will fall upon. In other words. it is relevant to know the start point of this present dissertation.

Firstly, in Table 3.2 will be presented the main features or requirements for the prototype, including:

- **FoV** - the angle which is covered by a sensor. In this case,for LiDAR, it is equal to the angle in which LiDAR signals are emitted [33].
- **Angular Resolution** - crucial for the determination of object width and shape [34].
- **Range** - LIDAR can detect objects at distances ranging from a few meters to 180 m, in this case;
- **Rotation velocity** - LiDAR housing frequency of rotation;
- **Dimensions** - LiDAR housing dimensions;
- **Temperature Range** - Automotive range of temperatures for LiDAR functioning.

Table 3.2 Bosch's LiDAR features.

System Main Features	FOV	300°x12°
	Angular Resolution	0.1
	Range	180m
	Frequency	10Hz = 600RPM
	Dimensions	120x180 mm
	Temperature Range	-40°C- 85°C
Scanning Subsystem	Scanning based	1D μMirrors
	Light Source	Fiber Laser
	Wavelenght	1550nm
Purpose	Highway Pilot	

In figure 3.23 it is possible to better visualise a sketch of Bosch's concept for the LiDAR solution. In Figure 3.23 (b) it is possible to understand that the FoV is 300°, even though the rotation is a complete 360° full circle. This is explained based on the fact that the FoV is limited in 60°, which correspond to the lateral support, which works as the non rotative part of the LiDAR prototype.

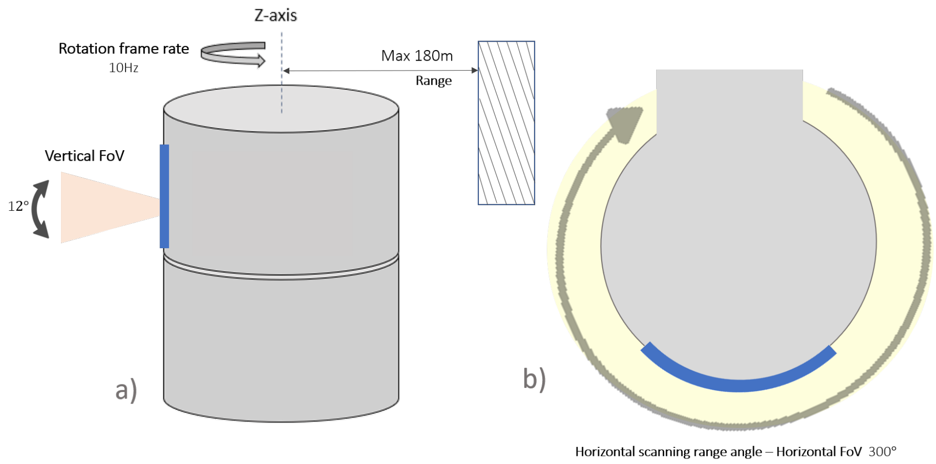

Figure 3.23 Bosch's LiDAR concept for the prototype (a)front view (b) Top view.

Putt differently, the lateral support, including the top and bottom bases, represented in grey in Figure 3.24, are fixed in the structure of a car, while the housing for the eletronic and optical components, represented in blue, rotates to provide the horizontal FoV (300°)) required. That said, and having the LiDAR system the need to monitorize the 360° environment around the car, two LiDARs would be needed to guarantee the full control of what is happening around the vehicle. This representation of Bosch's LiDAR concept was the starting point for, either, the development of a cleaning system, the theme of the present dissertation and for the housing development. As previously mentioned the housing development for the optical and eletronical components is being carried out at the same time and both systems, the housing and cleaning, need to be compatible for a functionable final solution.

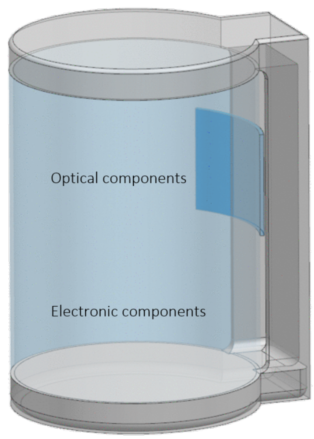

Figure 3.24 Starting point for the Bosch's LiDAR concept for this dissertation.

Chapter 4

Cleaning Status

This chapter summarises several automotive suppliers and OEMs that have created their own patents detailing several methods of cleaning of opto-mechanic sensors.

Automotive industry has some current patents which covers different properties regarding cleaning methods. With the intention of analysing the existing ones in this market, by the automotive suppliers and OEMs, a selection of a few patents was grouped and distributed by different significant criteria for this subject, see Table 4.1.

Table 4.1 Several cleaning patents of automotive suppliers and OEMs.

		Air Flow	Wiper	Nozzle	Heating wire	Other
Automotive Suppliers	Bosch	DE10012004(A1)			DE10149337(A1)	US2013094086(A1) Minimizing dirt by choosing mounting location
	Continental	WO2016/004936(A1)	WO2015/003705(A1)	US2013146577(A1)		
	Valeo		WO2016116568(A1)	US2016103316(A1)		
	Denso			DE102012218583(A1)		US2017008372(A1) Blowing wind
	TRW					
	Murata		US2016315564(A1)		WO2016072204(A1)	JP2001301527(A) Cover
OEMs	Bayerusche Motoren Werke			DE102015204072(A1)		
	Daimler		DE102016006039(A1)	DE102016010441(A1)		DE102015006287(A1) Cleaning mechanism
	Volkswagen			DE102010025193(A1)		DE10037222(A1) Cover for camera
	Toyota			DE102016200835(A1)		
	Nissan			JP2015214199(A)		
	Ford	DE102016106870(A1)	DE202016103138(U1)	US2014270379(A1)		DE102014218984(A1) Method for autonomous car

Quoting John Krafcik, Waymo's CEO, *"One of the things to really focus on is ensuring* *four-season robustness. And that means that sensor cleaning is a critical, up-front design parameter [for LiDAR]*".

Cleaning sensors may sound like an ordinary engineering task, but it is a crucial one if the huge investments being made nowadays in the self-driving technology are ever really going to pay off. If a car is disabled by getting sprayed with road salt or driving through a cluster of mayflies, it will not perform as expected.

The basic functions of the self-diagnosis of a distance sensor include the detection of the degree of contamination of the sensor at the transmitter and receiver. This signal results, in most of the cases, not to a request to clean with the sensor, but the signal can easily be used to trigger an automatic cleaning.

Robert Bosch GmbH has acquired several patents regarding active cleaning technologies for optical components in motor vehicles. These patents are detailed below in Section 4.1.

4.1 Active cleaning technologies patents

4.1.1 Device for keeping optical elements clean

DE10012004A1

A device for cleaning optical elements in motor vehicles, especially sensor or camera covers. This is done by applying a directed stream of gas to the transparent cover in such a way that when the cover moves relative to the surroundings no ambient atmosphere reaches the surface of the cover. In a further refinement, a cleaning nozzle and a heater for the cover can be provided, in order to also be able to perform cleaning when soiling has occurred during stationary operation and to remove icing at low temperatures [35] [36].

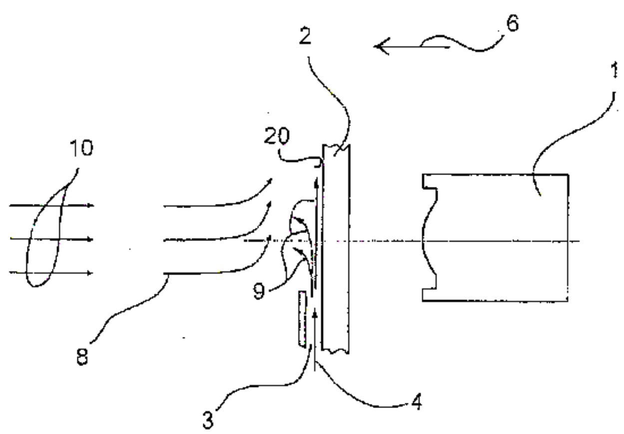

Figure 4.1 Schematic side view of an embodiment of the device for keeping optical elements clean [36].

4.1.2 Device to be Mounted on the Front Part of a Motor Vehicle

DE10149337A1

A device for a front-end component part of a motor vehicle, behind which a radar transmitter/receiver is fastened in such a way that the latter is not visible from the front. In winterish surroundings, ice and snow deposits can occur, it is possible to remove and/or prevent these precipitation deposits in the front component part [35] [37].

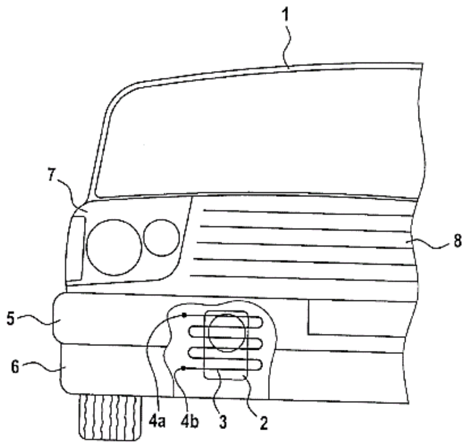

Figure 4.2 First exemplary embodiment of the device to be mounted on the front part of a motor vehicle [37].

4.1.3 Sensor Device for Determining the Degree of Wetting and/or Soiling on Window Panes

DE19746351A1

A sensor device for determining the degree of wetting and/or soiling of a pane in a motor vehicle is provided. The sensor device detects the coating of moisture on the outer side of the pane. The device includes a reflector positioned in the pane that directs a beam through it and also includes a light filter which absorbs a selected wavelength of sunlight [35] [38].

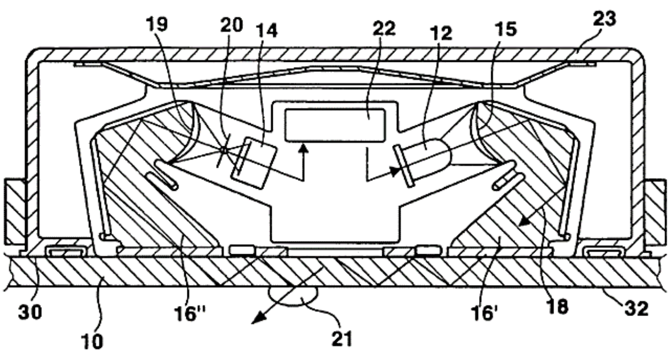

Figure 4.3 Cross section of an optical rain sensor mounted on a glass pane [38].

4.1.4 System and Method to Minimise Contamination of a Rear-View Camera Lens

DE19746351A1

A system for minimising the accumulation of debris on a lens of a rear-view camera of a vehicle, wherein the lens includes a formed channel having a first end and a second end. The first end is in fluid communication with an external airstream effected by the vehicle's movement. The second end is disposed adjacent to the lens and is configured to a direct portion of the passing airstream over the lens surface [35] [39].

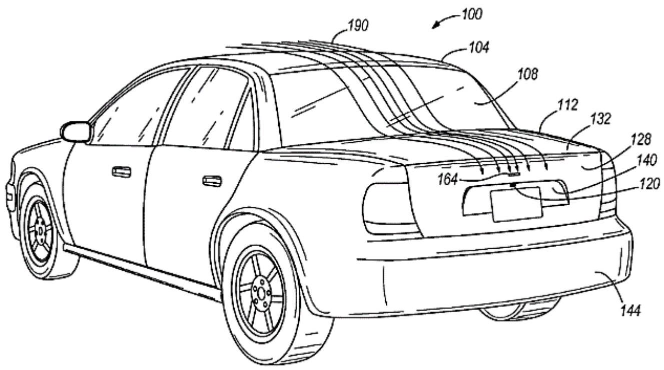

Figure 4.4 Perspective view of a vehicle showing the system for cleaning the lens of a rear-view camera integrated with the trunk of the vehicle [35] [39].

After having presented the several existing patents and methods to ensure the cleaning of opto-mechanic sensors it is relevant to understand which will be the contaminants which will pollute the surface of a car. This topic will be explore in Chapter 5. It is important to point out that all the previous existing solutions was done to provide sufficient knowledge about the technologies involved in the core problem.

Chapter 5

Surface Contamination of cars

This Chapter explores the problem of surface contamination of cars, which represents a major engineering challenge to vehicle manufacturers, operators and users. The deposition of water and solid contaminants on to the car surfaces is also strongly influenced by vehicle aerodynamic effects. Airborne water droplets falling as rain or lifted as spray by tyres interact with wakes, vortices and shear flows and accumulate on vehicle surfaces as a consequence [40]. The focus of this Chapter relays on an ***Environment Analysis****, more precisely, which conditions may a car be exposed to, Section 5.1; in Section 5.2,* ***Pollution Detection****, understand how can that pollution be detected by the car in order to activate the cleaning solution for the LiDAR System. Finally, in Section 5.3,* ***Types of Pollution****, considering the Environment Analysis previously done, the goal is to study the possible contaminants to which a car may be exposed.*

5.1 Environment Analysis

Several publications report that LiDAR sensors are specially sensitive to weather phenomena. In severe weather conditions, contaminants like water or particles from road dirt attach on the outer surfaces of a vehicle [25] [41].

Regarding environmental conditions, the POW will be subjected to high and low temperatures. This temperature range will be useful in the material selection phase for, firstly, the POW material and, secondly, the one for the active cleaning solution, which directly interacts with the POW itself, since they have to be stable materials at different temperatures and compatible with each other. Rain, fog and dust are other environmental conditions to have into account, since the accumulation of humidity and soiling on the surface may affect the transmission of the laser beams and consequently the optical performance of the POW and, consequently, the entire LiDAR system. These obligations are defined in Section 3.5 and must be complied by all the Automotive Industry.

In relation to road surface conditions, it is important take into account that there are different types of pavement to consider, revealing different risks for the POW component:

Eroded asphalt is usually the pavement of urban roads. Usually on this type of roads, there are bad road conditions (e.g. holes) that may cause vibrations and impacts on the component.

Typical asphalt is usually the pavement of the highway. Usually this type of road presents very good conditions. However, due to the high speed that is allowed on this type of road, the impact of insects or other type of detritus present in the environmental, as well as undesirable but frequently found small rocks can seriously pollute or even damage permanently the surface of the component.

Cobblestone is another type of pavement, which is usually the floor of the country roads. Such as in "eroded asphalt", this type of pavement can cause vibrations and impacts on the component. "Unpaved road" it characterised by the presence of small debris (e.g. stones and sand) that can be projected against the POW, and damage the surface.

So, it is important that the POW and the possible exposed part of the active cleaning solution exhibit sufficient mechanical properties, such as, impact and scratch resistance, in order to avoid damaging of the components and consequently the performance of the system.

Exceptional Conditions

A small bump or collision between vehicles, the release of heavy debris against the surface of the POW are some of the exceptional scenarios at which the component may be exposed to. These scenarios, although not occurring daily, must be considered, since they can influence the performance of the components. Therefore, it is important, in addition to good mechanical properties, that they also present good chemical resistance preventing any undesirable property change (transparency loss or other) due to contact with different chemicals.

5.2 Pollution Detection

To fully automate the cleaning process, the cleaning system has to be supported by a pollution detection system to trigger the process. LiDAR systems use a source of light to illuminate the sensor's field of view containing objects to be detected. From the objects in the sensor's field of view, a certain part of optical power is reflected back towards the sensor where the signal is detected by an optical receiver. In most automotive laser systems, optical signal transmitters and receivers are located close to each other or even use the same optics in a coaxial beam configuration for successful detection. For automotive applications optical receivers, PIN-photo diodes, avalanche photo diodes (APD) are typically used.

Compared to PIN-diodes, APDs usually provide a superior signal-to-noise ratio (SNR) and, consequently, the choice falls upon them.

For the differentiation between water and solid contaminants the signal of the photodiodes is necessary. These differences are seen by separated peaks in the analysis of the APDs data.

5.3 Types of pollution

The influence of atmospheric conditions on the reliability of LiDAR data has, still, a lot to be explored. This, probably, comes from the fact that traditional applications of LiDAR measurements are surveying and, consequently, the person that operates the system can choose good atmospheric conditions to perform the measurements. The situation radically changes with the integration of LiDAR systems into autonomous vehicles. The vehicle must be able to operate in a safe manner under harsh atmospheric conditions such as fog, rain, or snow, and, naturally, with contaminants on its POW surface [42] [41].

In this dissertation the contaminants to be used to simulate and test the POW material will be:

- Salty saturated water - To simulate corrosion on surface;
- Arizona dust - To simulate naturally occurring compounds which motor vehicles are commonly subjected to. Its composition is presented in Table 5.1;
- Yogurt - To simulate animal's biogenic material.

Table 5.1 Composition of Arizona Test Dust by percent weight calculated from 100 mapped frames for EDS analysis [43].

	Chemical composition (% weight)	
Chemical	Manufacturer	EDS
SiO_2	68–76	66.9
Al_2O_3	10–15	21.9
Fe_2O_3	2–5	4.2
CaO	2–5	3.7
MgO	1–2	4.3
TiO_2	0.5–1.0	2.2
K_2O	2–5	2.7

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Chapter 6

Concept Development

This chapter aims to exhibit the progress and results obtained through the concept development phase of the thesis. The practical part of this thesis is divided into two parts: the first part corresponds to the development of the active solution. The second part corresponds to the characterisation of promising materials for the POW. The concept development phase followed the research phase.

6.1 Concept Generation

To introduce the concept generation of the LiDAR cleaning system, a functional mapping is constructed with a Functional Means Tree, see Appendix B.1. To easily comprehend the mapping, it was divided per sectors, as seen below in this document, from Figure 6.1 to Figure 6.5.

To build the mapping, all the possibilities were identified in order to understand the several possibilities, without limiting the potential final solution. Based on online searches, patent searches, research in Bosch's projects and deliverables, several solutions were studied to gain conscience about what already existed and to, at last, be able to create the best solution possible.

The preliminary step towards the development of a cleaning LiDAR system is to understand which are the inherent stages to cleaning a sensor. Evidently, what comes to mind, is engineer a cleaning LiDAR system, so to speak, as repellent as possible to pollution, and, naturally, an active solution, also, to eliminate any eventual type of pollution accumulated.

Therefore, as seen in Figure 6.1, the cleaning method was categorised in terms of action: passive or active. In other words, a passive solution implies something that is already built in the system and does not require additional energy or interaction to work. For instance, a coating is categorised as an passive solution. On the other hand, active solutions are also essential, whenever the passive solution is not sufficient or an extra action is necessary to reestablish the sensor previous conditions, before being polluted.

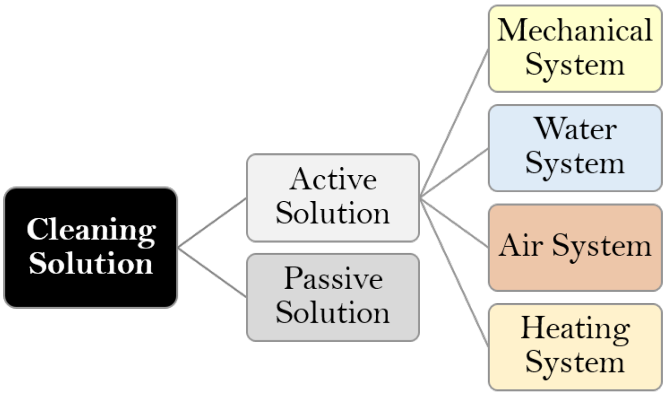


Figure 6.1 Cleaning solutions Functional Tree.

Still in Figure 6.1, inside the active solutions, it is possible to define four sub-systems: mechanical, water, air and heating systems. Each one of them will be explored later in this document to better comprehend the complete Functional Means Tree.

Starting by the first sub-system, from Figure 6.2, the Mechanical System will ideally detach and remove obstructions from the POW, by physical means. The two options considered were a wiper and a brush, as seen in Figure 6.2. However, the chosen option, to move forward with, was the wiper. The reason behind this decision was the possibility to remove rain, snow, ice, washer fluid, water, and other debris, whereas, with a brush, the possibility to remove rain and, in general, water drops is excluded.

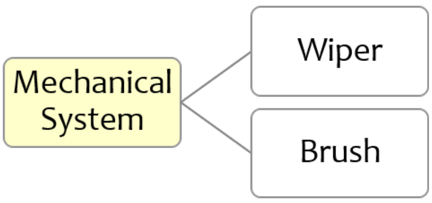


Figure 6.2 Mechanical System Tree.

Regarding the water system, which scheme is presented below, in Figure 6.3, it is relevant to understand what entails the integration of a water system in the cleaning system prototype, namely the storage, transport, distribution and collection.

The integration of a water system presupposes the existence of a water reservoir. This can be included in the cleaning solution to be designed or could come from an existing water reservoir in the vehicle. Both possibilities do have advantages and drawbacks. The use of a reservoir, already included in the car structure, saves the space for the integration of an extra one, but, on the other hand, brings the problem to its integration in the vehicle structure. Similarly, the storage of an extra reservoir included in the cleaning solution brings up some questions, such as, for instance: how much space will occupy, the amount of water inside the reservoir, how many times can we use the reservoir before filling it again and how can the reservoir be filled.

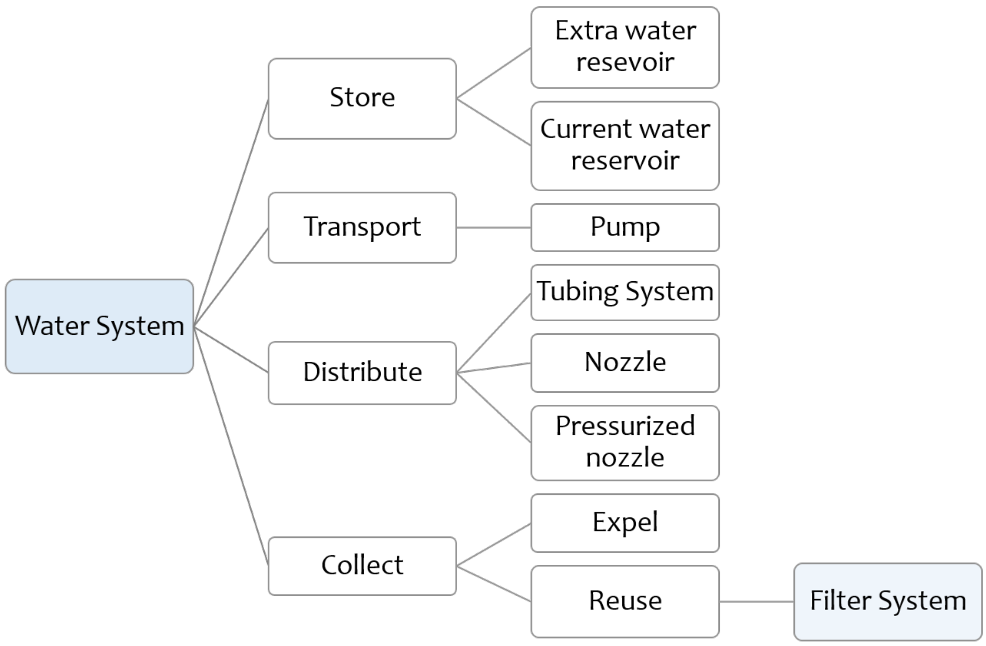


Figure 6.3 Water System Tree.

Also, in the previous scheme, the transport, distribution and water collection is mentioned. In order to transport water from a point A to a point B a water pump might be considered. Its distribution could be done through a tubing system, with or without a pressurised nozzle. After being ejected, the water might be expelled or reused. If the option is to reuse water, a filter system may be considered.

Another sub-system presented in Figure 6.1 is the air system.

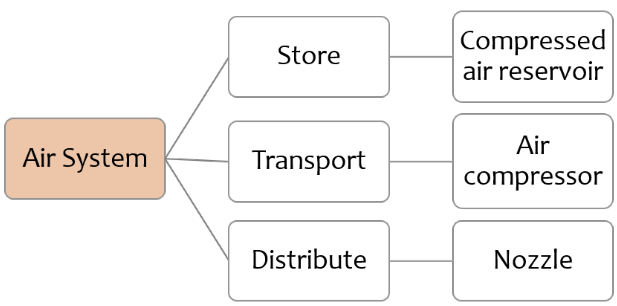


Figure 6.4 Air System Tree.

In an air system, the storage of air requires the existence of a compressed air reservoir. After that, it passes through a air compressor and exits through a nozzle.

Finally, the last sub-system seen in Figure 6.5, Heating System, contemplates the generation and exchange of heat. The generation of heat might occur in a heat source in the car or directly through electricity. Besides its generation, heat exchange might happen throughout a heat exchanger, calorifier, heat pump, in-line/pipe heater or immersion resistance.

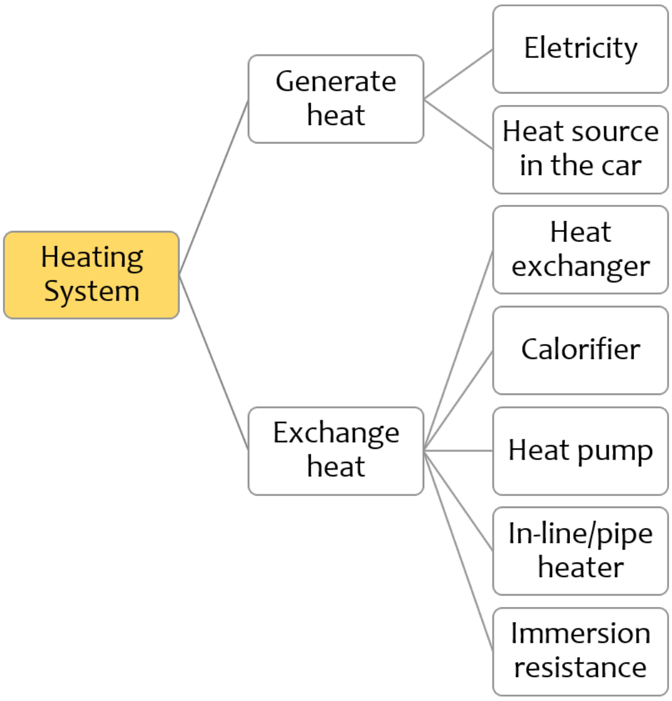


Figure 6.5 Heating System Tree.

With all this options and sub-functions in mind, in Subsection 6.1.1, the initial concepts, developed in the *Generation of Concepts* phase will be presented through simple drafts or sketches with a brief explanation of each one. All of the previous drafts are going to provide guidance to the *Screening and Concept Selection* phase and, consequently, to the design of the chosen and final concept.

However, firstly, it is important to recall Bosch's LiDAR idea for the new prototype. In a summarised manner, this prototype will be built on the "Rotating Housing" concept, which means that there is a fixed support, numbered with a "1" in Figure 6.6, which purpose is to work as the LiDAR structure, upon which the rotating housing, numbered with a "3" in the following picture, will be placed. As the name suggests, the *Rotating Housing* rotates the optical system placed inside it, to acquire the horizontal information needed for the 3D mapping. Also, placed inside the housing are the electronic components. Numbered with a "2" is the Protective Optical Window, which rotates with the *Rotating Housing*.

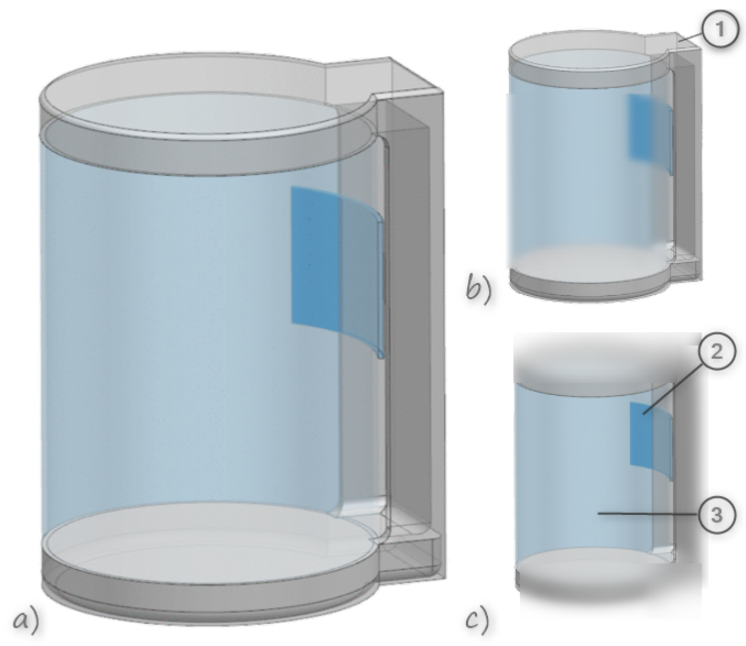


Figure 6.6 *Bosch's* LiDAR concept.

At this point, with *Bosch's* LiDAR concept in mind, the ideas for the Cleaning System system will be present ahead in Section 6.1.1.

6.1.1 Generation and Description of Concepts.

A sketch and a short description of each concept are shown below.

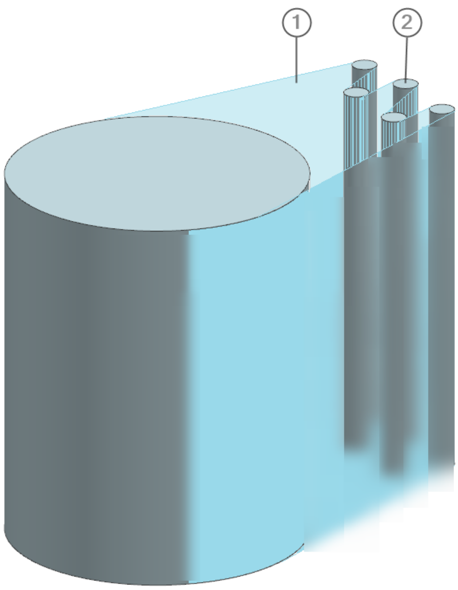


Figure 6.7 Sketch of the concept 'Rotating Film'. (1) Film (2) Stoppers.

Rotating Film

The concept consists in a protective film, with good optical properties, which rotates whenever the transmittance is not the maximum. In other words, whenever it is polluted, the film, tensioned in the stoppers, rotates and replaces the polluted film for a new one.

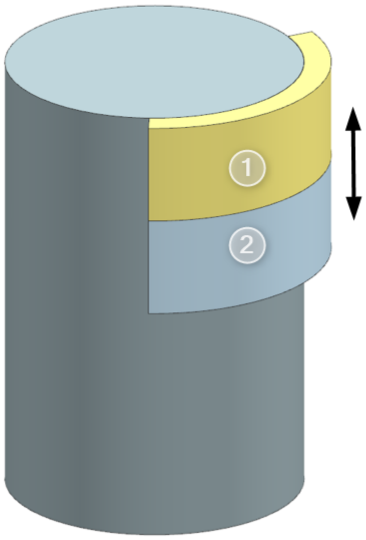


Figure 6.8 Sketch of the concept 'Up and Down Washer and Dryer'. (1) Washer (2) Dryer.

Up and Down Washer and Dryer

The concept 'Up and Down Washer and Dryer' consists in two accessories for cleaning: a washer (1) and a dryer (2). Whenever the cleaning is activated the dryer and the washer go up and down to the defined height of the protective window. Whenever the cleaning is not needed, the position of both accessories is the one where they are both not blocking the FoV.

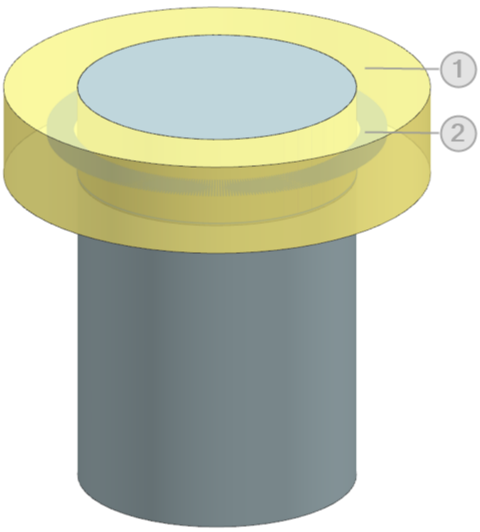


Figure 6.9 Sketch of concept 'Ring Brush'. (1) Ring-shaped Support (2) Brush.

Ring Brush

The concept 'Ring Brush' consists in ring-shaped accessory with an inside brush. Whenever the cleaning is activated the washer and the dryer go up and down to the defined height of the protective window. Whenever the cleaning is not needed, the position of both accessories is the one where they are both not blocking the FoV.

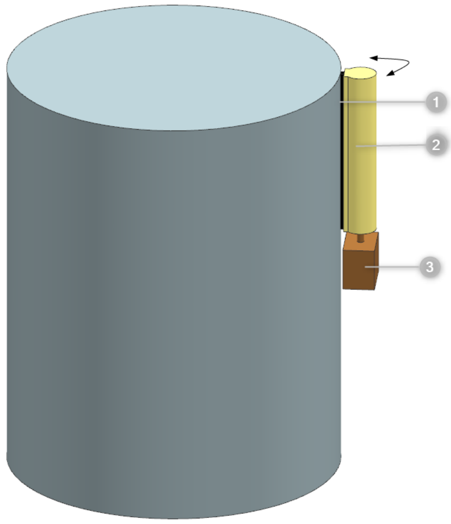


Figure 6.10 Sketch of concept 'Rotating Wiper' (1) Wiper (2) Wiper support (3) Servomotor.

Rotating Wiper

The concept 'Rotating Wiper' consists in a wiper, which rotates to lean against the protective window, whenever cleaning the protective window is required. The cleaning is assured per the wiper (1). The wiper rotation is enabled per the motor (3) which is connected to the wiper support (2).

6.2 Screening and Concept Selection

In order to be able to select the most suitable concept to proceed with the design it was used a Pugh Matrix. It allows the comparison of a number of design candidates leading, ultimately, to the one who best meets a established set of criteria. This matrix encourages comparison of several different concepts against a base concept, creating stronger concepts and eliminating weaker ones until an optimal concept is finally reached, among all alternatives [44]. The Pugh matrix is, also, helpful because it does not require a great amount of quantitative data on design concepts.

The Pugh Matrix, shown in Figure 6.2 takes several factors into account to reach the final decision. However, firstly, in Figure 6.1 is presented the weight(%) of each criteria. The Pugh Matrix with the Evaluation of weighting factors and the Evaluation of beneficial variants are, both, attached to this dissertation in Appendix

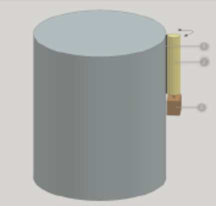
Table 6.1 Evaluation of weighting factors.

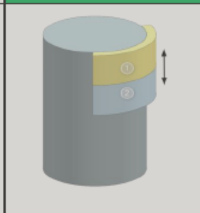
Scoring for pairwise comparison of criteria:

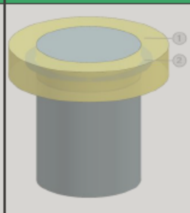
2	Red criterion more important than blue criterion
1	Red criterion has same importance as blue criterion
0	Red criterion less important than blue criterion

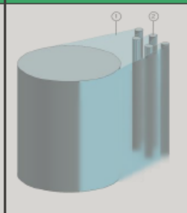
		Ease of integration into LiDAR concept	Box volume fulfillment	Lenght of cleaning process	Risk of damaging the POW	Assembly and instalation	Possibility to work at the same time as the cleaning	Resources used (Heat, water, others)	Possibility of polution re emerging			
No.:	Criterion	1	2	3	4	5	6	7	8	Sum	weight(%)	Rank
1	Ease of integration into Bosch LiDAR concept		0	2	0	2	2	2	1	9	16,1	4
2	Box volume fulfillment (including interface/mounting components)	2		2	0	1	2	2	1	10	17,9	2
3	Lenght of cleaning process	0	0		0	1	1	2	0	4	7,1	6
4	Risk of damaging the POW	2	2	2		2	2	2	2	14	25,0	1
5	Assembly and instalation	0	1	1	0		0	1	0	3	5,4	7
6	Possibility to perform its function at the same time as the cleaning	0	0	1	0	2		2	0	5	8,9	5
7	Resources used (heat, water, others)	0	0	0	0	1	0		0	1	1,8	8
8	Possibility of polution re emerging	1	1	2	0	2	2	2		10	17,9	2
										56	100,0	

Table 6.2 Evaluation of beneficial variants.

Reference


Variant 1


Variant 2


Variant 3


			Reference			Variant 1			Variant 2			Variant 3		
No.	criteria	weight factor G	Score B	Reason	G x B	Score B	Reason	G x B	Score B	Reason	G x B	Score B	Reason	G x B
1	Ease of integration into Bosch LIDAR concept	16,1	0	reference	0,0	-1		-16,1	-1		-16,1	0		0,0
2	Box volume fulfilment (including interface/mounting components)	17,9	0	reference	0,0	-1		-17,9	-1		-17,9	-1		-17,9
3	Lenght of cleaning process	7,1	0	reference	0,0	-1		-7,1	0		0,0	0		0,0
4	Risk of damaging the POW	25,0	0	reference	0,0	0		0,0	0		0,0	-1		-25,0
5	Assembly and instalation	5,4	0	reference	0,0	-1		-5,4	0		0,0	1		5,4
6	Possibility to perform its function at the same time as the cleaning	8,9	0	reference	0,0	-1		-8,9	0		0,0	1		8,9
7	Resources used (heat, water, others)	1,8	0	reference	0,0	-1		-1,8	0		0,0	-1		-1,8
8	Possibility of polution re emerging	17,9	0	reference	0,0	0		0,0	0		0,0	-1		-17,9
	sum	100,0		overall score:	0,0		overall score:	-0,57		overall score:	-0,34		overall score:	-0,48

The viability of the outcome is fundamentally dependent on an appropriate set of criteria/requirements. The requirements established for this selection and an explanation of each criteria applied in the Pugh Concept Selection Matrix is presented below.

- **Ease of integration into LiDAR concept** - Considering Bosch's LiDAR concept, presented in the beginning of the current chapter, this criteria evaluates how adaptable are the brainstorming ideas to it;
- **Box volume fulfilment** - This criteria defines if there is a need to change Bosch's LiDAR housing dimensions;
- **Lenght of cleaning process** - This criteria establishes the duration of the cleaning process to reset the optimal transmission conditions;
- **Risk of damaging the POW** - This criteria evaluates if the concept presents risk for damaging the Protective Optical Window during the functioning of the cleaning system;
- **Assembly and installation** The time of assembly and installation should be kept as low as possible. Fewer and easier steps during the process of assembly and installation are preferable;
- **Possibility to perform its job at the same time as the cleaning** - This criteria evaluates if, for a given concept, it is possible to perform its function - acquire 3D information - and perform the cleaning, simultaneously, or, otherwise, the LiDAR has to stop for the cleaning process be triggered.
- **Resources consumption** - This criteria takes into account if there is, for a given concept, the need to use a certain resource (water, air, film, etc).

- **Possibility of pollution reemerging** - The present criteria indicates if there is a chance for the pollution previously cleaned to reemerge.

Making a pairwise comparison allows for subjective opinions about one alternative versus another to be made more objective. Thereby, after applying the Pugh Matrix, the conclusion is that the concept defined as *Reference* has the best result.

- Reference *Rotating Wiper* vs Variant 1 *Up and Down Washer and Dryer*

Making the comparison between the reference, *Rotating Wiper*, and Variant 1, *Up and Down Washer and Dryer*, the integration of the *Rotating Wiper* would be easier because the there is a possibility to include the mechanism in the lateral support of Bosch's LiDAR concept. Regarding the box volume fulfilment, it is expectable that the *Rotating Wiper* concept would easily be incorporated in the dimensions assigned for the new prototype. In terms of the cleaning process lenght it is predictable that the Rotating Wiper's would be shorter and could be performed at the same time as the LiDAR data acquisition. In relation to the risk of damaging the POW, in *Reference* there is the possibility to lean against the POW when the cleaning is needed, or not, whenever the transmission is good, which translates into a positive point comparing to the Variant 1. Regarding the resources used, the Rotating Wiper also wins in this segment because there is no need to additional resources. Finally, in Variant 1, considering that there is a incorporated brush that goes up and down to the POW height, there is a possibility of some kind of pollution to stick to the brush and reemerge.

- Reference *Rotating Wiper* vs Variant 2 *Ring Brush*

Establishing the comparison between the reference, *Rotating Wiper*, and Variant 2, *Ring Brush*, the integration of the *Rotating Wiper* would be easier because there is a possibility to include the mechanism in the lateral support of Bosch's LiDAR concept, Regarding the box volume fulfilment, it is expectable that the *Rotating Wiper* concept would easily be incorporated in the dimensions assigned for the new prototype, without changing the concept itself. In terms of the cleaning process lenght it is predictable that the Ring Brush's would be longer and could not be performed at the same time as the LiDAR data acquisition because the Ring Brush, would, at a certain point, block the LiDAR 360○ FoV. In relation to the risk of damaging the POW, the previous advantage of Rotating Wiper prevails. The resources criteria makes the Rotating Wiper a better choice also because there is no need to additional resources. Finally, in Variant 2, considering that there is a incorporated brush there is a possibility of some kind of pollution to stick to the brush and reemerge.

- Reference *Rotating Wiper* vs Variant 3 *Rotating Film*

Finally, comparing the last concept, and Variant 3, *Rotating Film*, the integration of the *Rotating Wiper* would be as easier as the *Rotating Film* because there is a possibility to include the mechanismx in the lateral support of Bosch's LiDAR concept, Regarding the box volume fulfilment, it is expectable that the *Rotating Wiper* concept would easily be incorporated in the dimensions assigned for the new prototype, without changing the concept itself. In terms of the lenght of the cleaning process, in Variant 3, there is no clear advantage face to the *Rotating Wiper*. With regard to the risk of damaging the POW, in this case even if directly, the film protects the POW from pollution it might affect the optical properties inherent to the POW, so it does not adds value. Regarding the resources, the maintenance of the film might be too frequent and, if not, there is a strong possibility to the pollution to reemerge.

From this standpoint, and having the *Rotating Wiper* as the solution to proceed with, it will be explained and detailed ahead in this Chapter the evolution of this concept until the final cleaning system prototype.

6.3 Concept Modulation

In this Section the *Prototype Functioning Principle* will be presented and fully detailed. Firstly, all the components will be introduced in the Section 6.3.1 to work as a detailed parts inventory. Its function and purpose in the prototype will be described further ahead. The 2D Drawings are attached in the Appendix E.

6.3.1 Parts Inventory

The CAD model consists in:

- Lateral Support

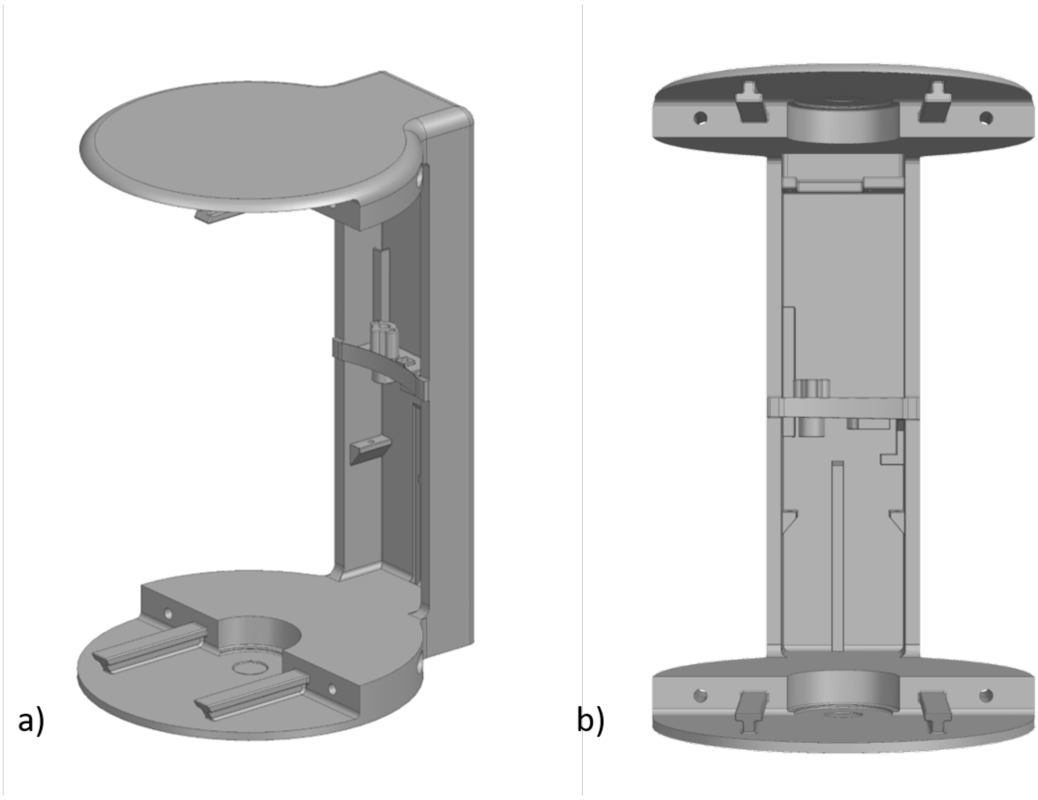


Figure 6.11 Lateral Support a) Isometric View b) Front View

- Plug-in socket;

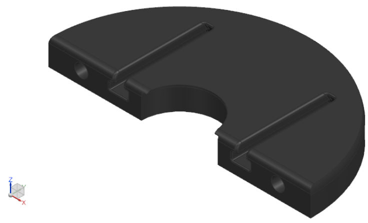


Figure 6.12 Top and bottom Plug-in Socket

- Wiper

Figure 6.13 Wiper

- a servo motor;

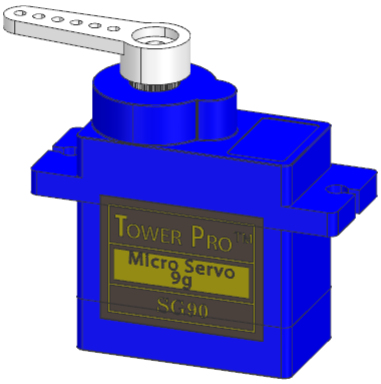


Figure 6.14 Servomotor for wiper rotation

- water pump;

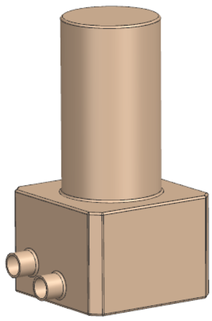


Figure 6.15 Water pump

- a reservoir;

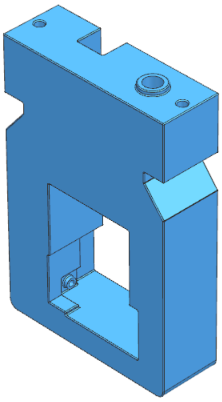


Figure 6.16 Water Reservoir

- Filter

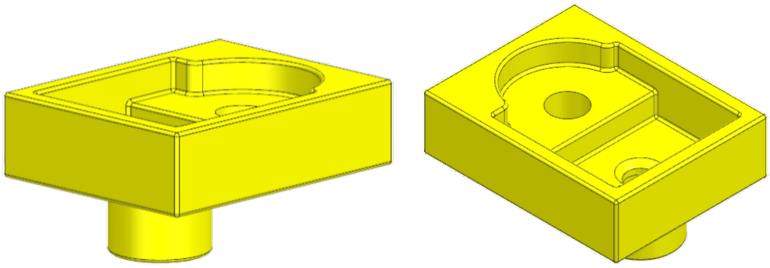


Figure 6.17 Filter Support

- a nozzle;

Figure 6.18 Nozzle

- Nozzle Support

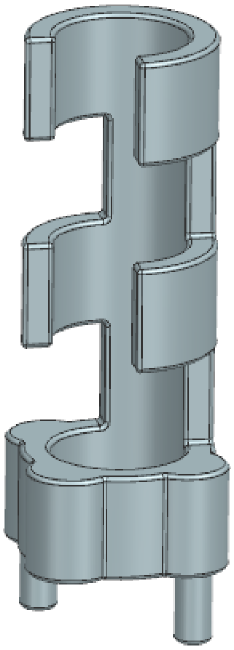


Figure 6.19 Nozzle Support

- a wiper support;

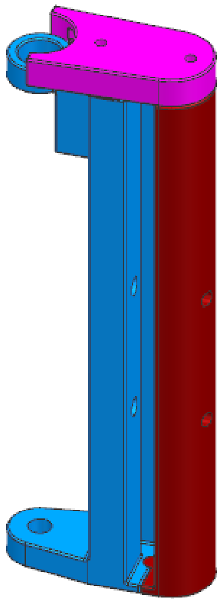


Figure 6.20 Wipper Support - Left Support (Blue); Right Support (Red); Arm Cover (pink).

- Polimeric Cover

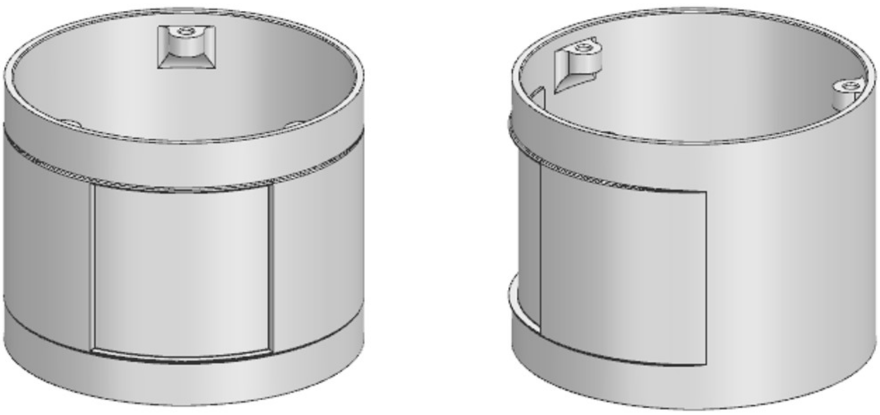


Figure 6.21 Polimeric Cover.

- Protective Optical Window

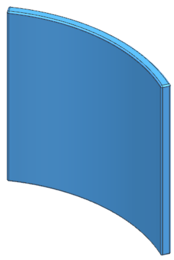


Figure 6.22 Protective Optical Window; Isometric View

- water circulation tubes;
- reservoir cap;
- 2 nuts and 2 screws for mounting the servo motor in the lateral support;
- 2 screws for mounting the left and right wiper supports to the arm cover;
- 2 screws for left and right wiper supports fixation to each other;
- a guidance pin for the wiper support,
- a particle filter;
- 2 fixation pins for the water reservoir;
- 4 inserts for the fixation between the lateral support and the plug-in sockets
- 4 screws and 4 inserts for the fixation between the lateral support and the plug-in sockets

All the relevant items will be explored and discussed later in this Section.

6.3.2 Prototype Function Principle

The active solution developed translates into the cleaning of the housing protection window through the action of the wiper on its surface. This cleaning can be combined with a water jet whenever necessary. Even though the option to include a water jet was not included in the *Concept Generation* phase, it was considered that its addition could strengthen the cleaning itself and, besides that, it was possible to fit in the prototype concept, as will be explained ahead in this document.

The principle of activating the active cleaning mechanism should be triggered by the APDs(Avalanche Photo Detectors), placed on the side support of the housing. Whenever the information received by the photo detectors is not the expected, the one which matches the maximum transmittance, it means that the interface between the optical system, located inside the housing, and the outside is compromised. This is the same as saying that the protection window is not in the ideal cleaning conditions it should be in. Therefore, measures to assure the ideal and expected conditions of the protective window are required.

Firstly, the wiper (7) is moved to the protection window in order to be able to clean it. This displacement corresponds to the rotation from the the zero position, in which it is not in contact with the protection window, to the actuated position, the position that ensures effective cleaning. In figure 6.23, it is possible to visualise both positions: a) the wiper detached from the protective window and in b) the wiper leaning against it .

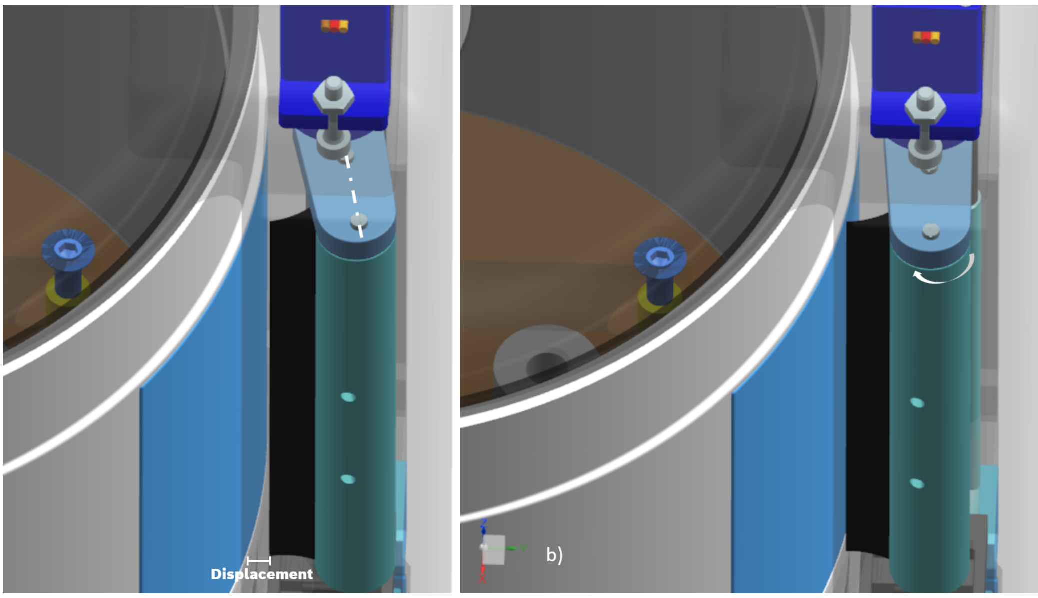


Figure 6.23 Wiper rotation scheme

This z-rotation is enabled per the servomotor (1) which controls the rotation of the servo motor arm (3), the arm cover (4) and both, the left (6) and right (5) wiper supports, in which the wiper (7) is mounted. All of the components previous mentioned are presented in Figure 6.24. In Figure 6.25 is schematised the wiper axis of rotation.

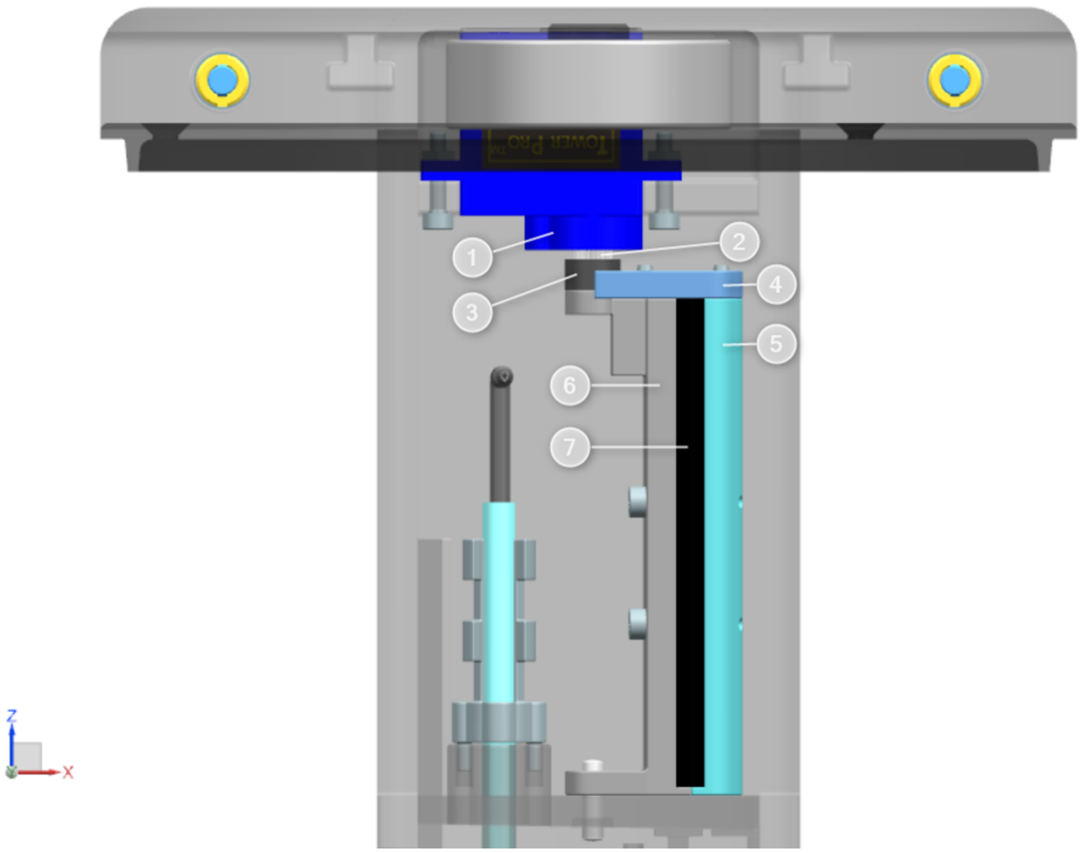


Figure 6.24 Wiper system controlled by the servomotor

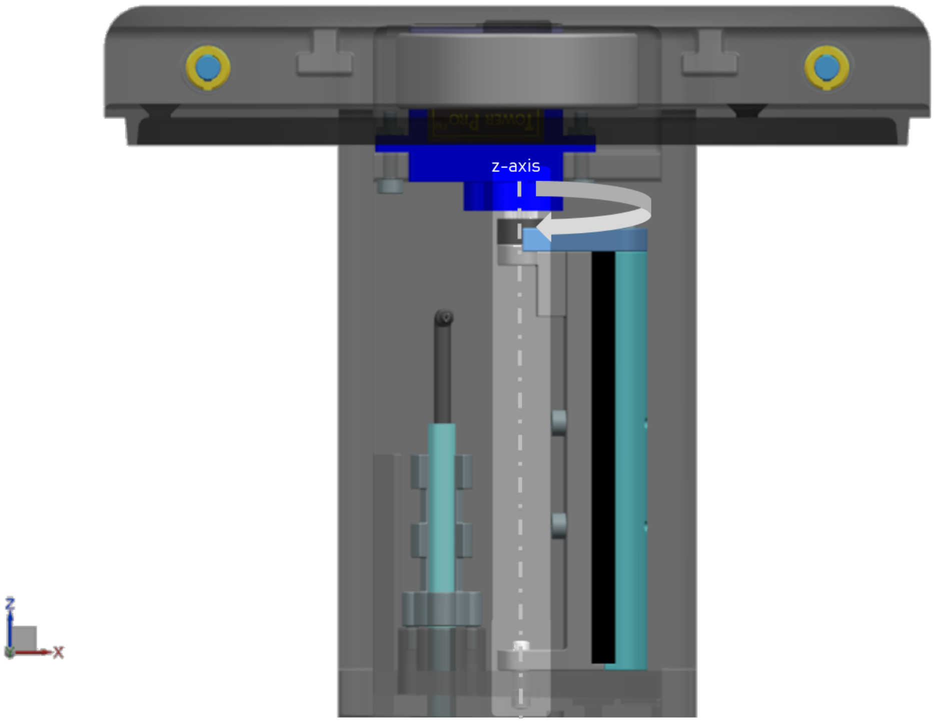


Figure 6.25 Wiper rotation axis

The pin, in the bottom of the wiper support, fixed in the intermediate level of the lateral support, works in an analogous way, to function as a guidance and define the z-axis in which the wiper rotates.

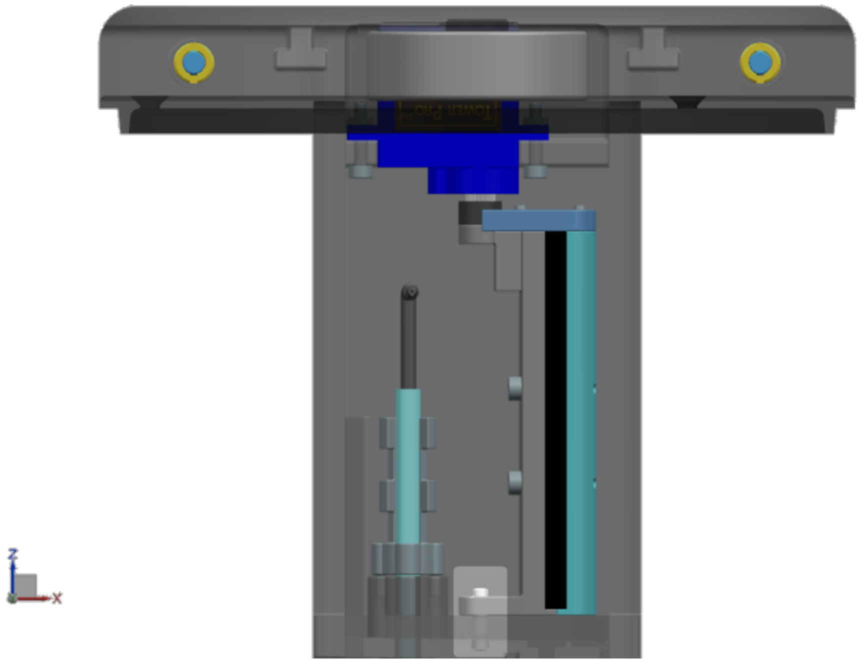


Figure 6.26 Guidance Pin to define the z-axis/wiper rotation axis

Whenever necessary, it is possible to eject a water jet with the intention of improving the basic cleaning, mentioned above. The flow direction is schematised in Figure 6.27. The water, from the reservoir (1), is pumped through the water pump (3), passing through the inlet tube (2), and conducted to the nozzle (5) by the outlet tube (4), as seen in Figure 6.28.

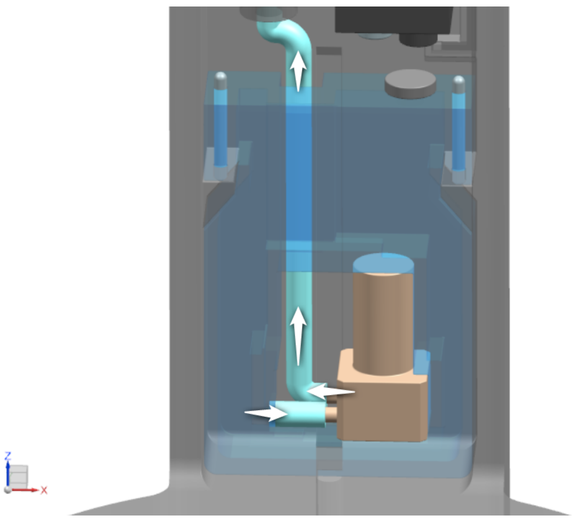


Figure 6.27 Circulating flow from the reservoir to the nozzle

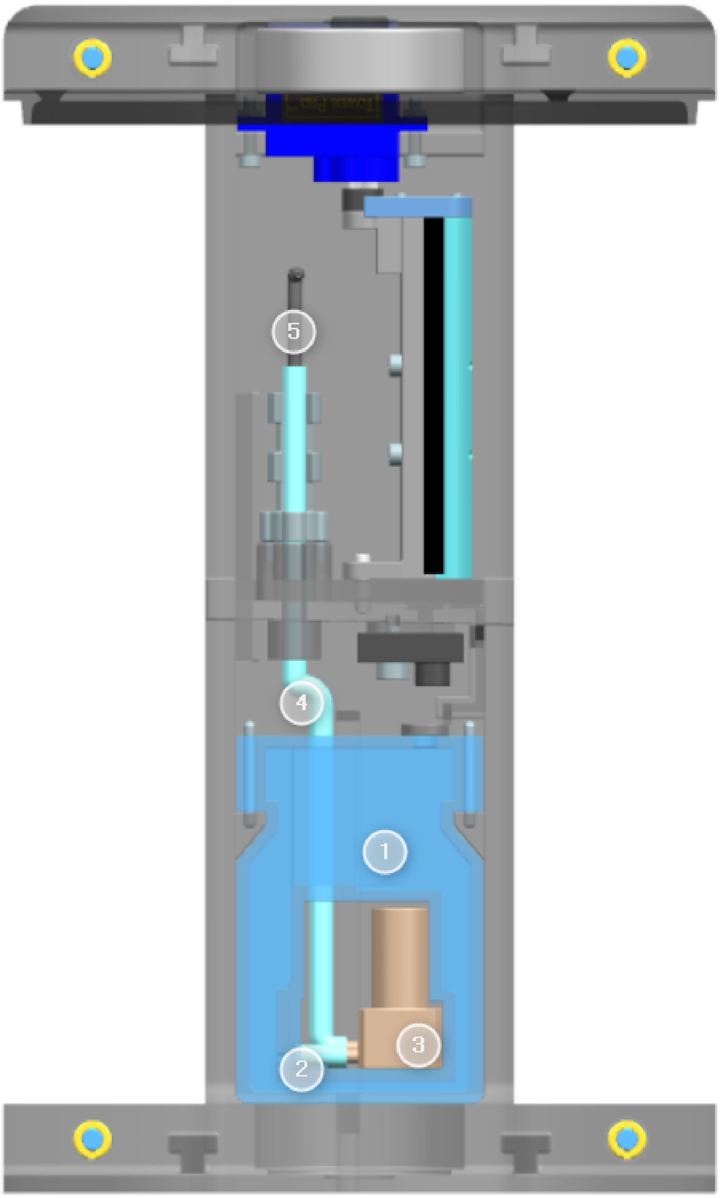


Figure 6.28 Water path from the reservoir to the nozzle

The reservoir is filled by removing the cap on top of it.

After being ejected from the nozzle to the protection window, the water is redirected with the help of the wiper to the slope of the intermediate level, Figure 6.29, and later reused or removed from the system.

Some water that can be ejected into the housing instead of the protection window is also partially redirected to the intermediate level. Although there are losses, since it is not possible to confine all the water to run off through the intermediate level, these are considered small and have no influence on the overall functioning of the LiDAR sensor.

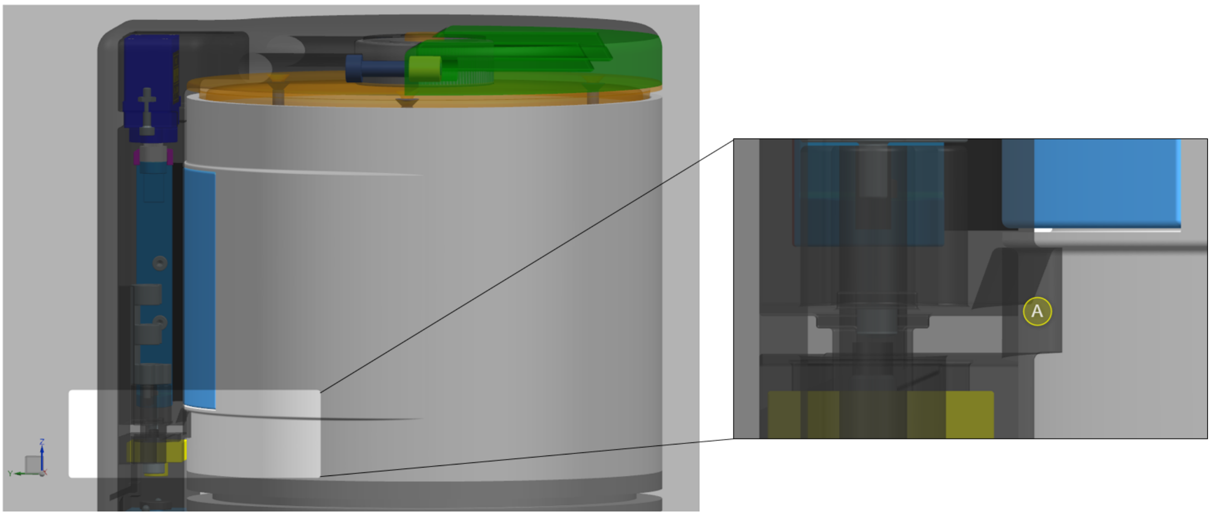


Figure 6.29 Intermediate level slope; A - slope detail

After being collected at the intermediate level, the water goes down to the lowest elevation of that same level, as seen in Figure 6.30, where, depending on the purpose (reuse or expulsion), it is redirected to the respective path, which will be better detailed below.

The filter support is represented in yellow in the following figures to better distinguish the lateral support from it.

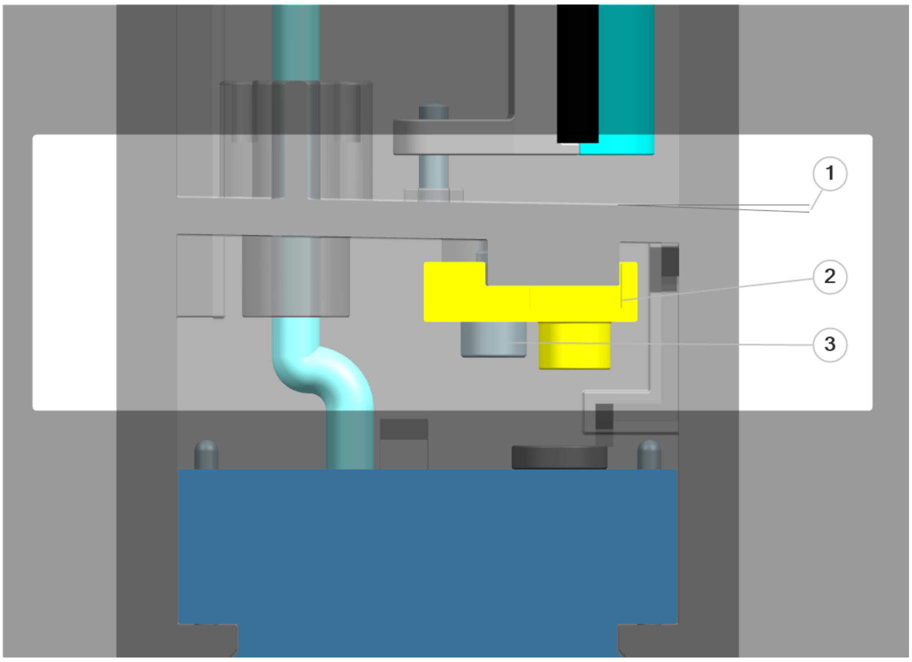


Figure 6.30 Filter System (1) One degree slope (2) Filter Support (3) Fixation screw

The previously mentioned paths the water might follow are two, and, both, are presented in Figure 6.31.

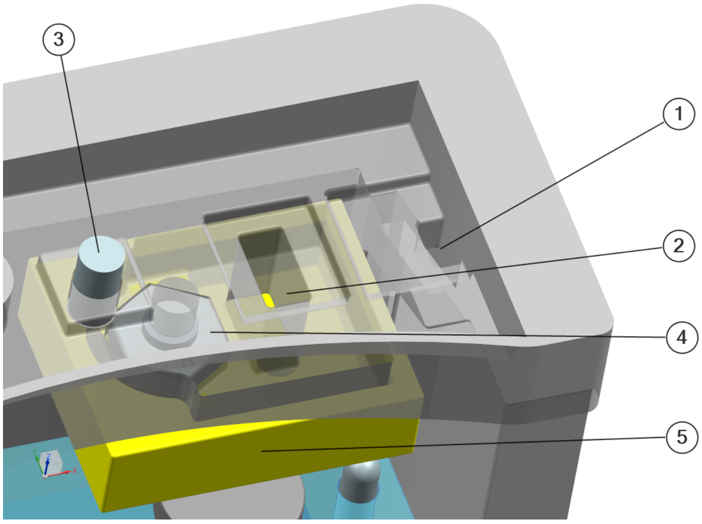


Figure 6.31 Clip Section (Plane z) Top view - Water paths (1) Path for water expulsion (2) Path for water reuse and filtration (3) Guidance pin (4)

Starting by the option to expel the water that falls on the intermediate level without reusing it, the area represented with number one in Figure 6.31 is the beginning of the path designed to that purpose. It is also needed to cover the second exit with a cap whenever it is not the option needed and vice-versa.

Considering the goal is to redirect the water to the system exterior, expelling it from the system, the trajectory after passing through the 'zone 1' is schematised in Figure 6.32 by the blue arrows. Cut views (A-A) and (B-B) are presented to easily understand the water trajectory since the intermediate level after being collected to it expulsion from the system

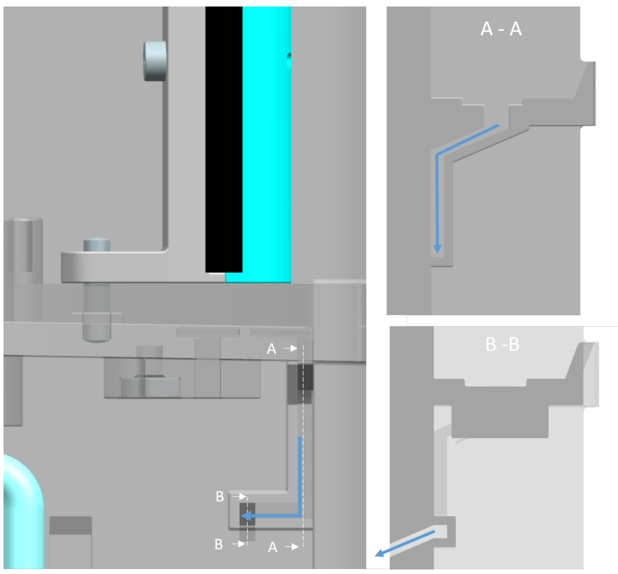


Figure 6.32 Water path from the intermediate level to the exterior without reuse

The back view of the lateral support, from where the water is expelled is presented in Figure 6.33.

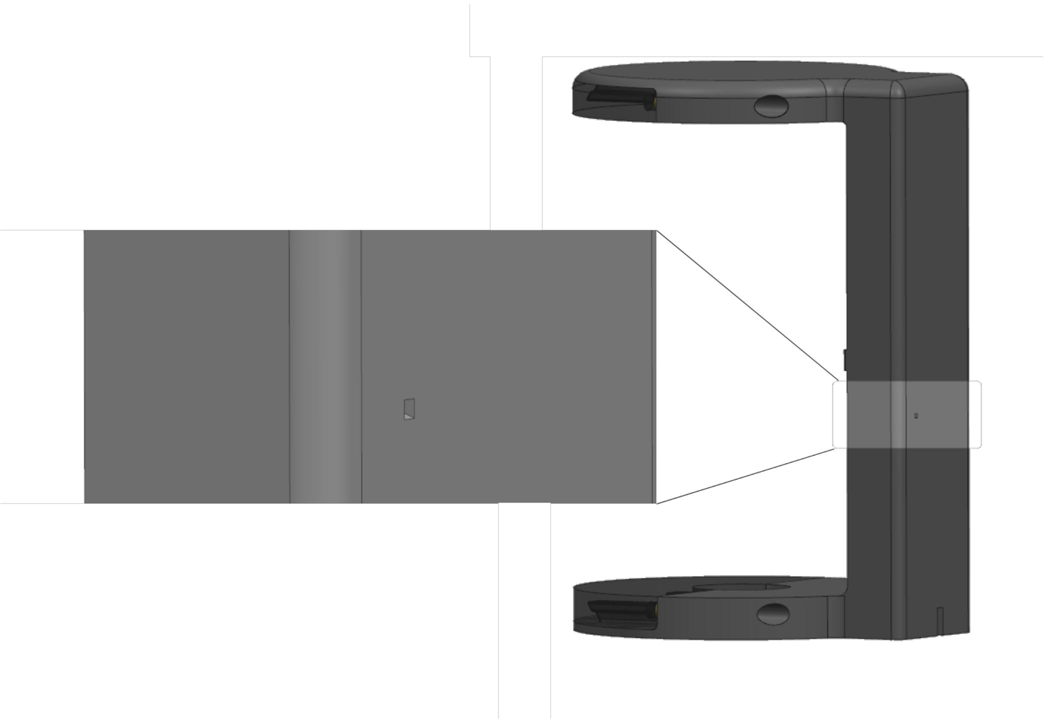


Figure 6.33 Back View - Lateral support with water exit detail

Knowing, already, one of the possible water exits, the second possibility will be presented and explained ahead.

Considering that the reservoir volume is limited, the possibility to reuse the water in circulation was taken into consideration.

Therefore, it was designed a filter system, whose entrance is represented in Figure 6.31 with the number two - path for water reuse and filtration.

Firstly, whenever the water, accumulated in the intermediate level of the lateral support, reaches the 'Zone 2', highlighted in Figure 6.31, it is redirected to the filter, positioned in the lowest level of the filter support.

The filter support and the filter position on it are schematised in Figure 6.34.

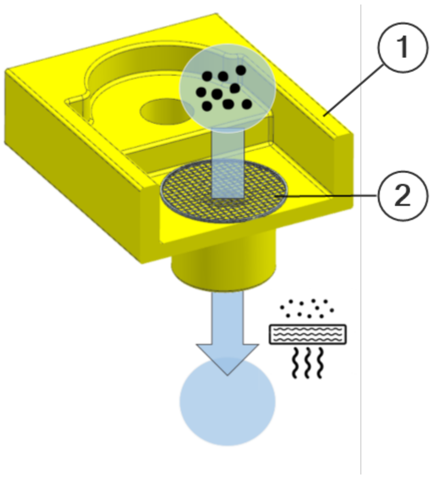


Figure 6.34 Section view - Filter System functioning scheme
(1) Filter Support
(2) Particle Filter

In Figure 6.35 a) it is shown how to fix the filter support. This is enabled through the use of a built-in nut in the lateral support, numbered with a "two" in the same figure. Insert the screw, number 4, securing it and the filter support with the built-in nut.

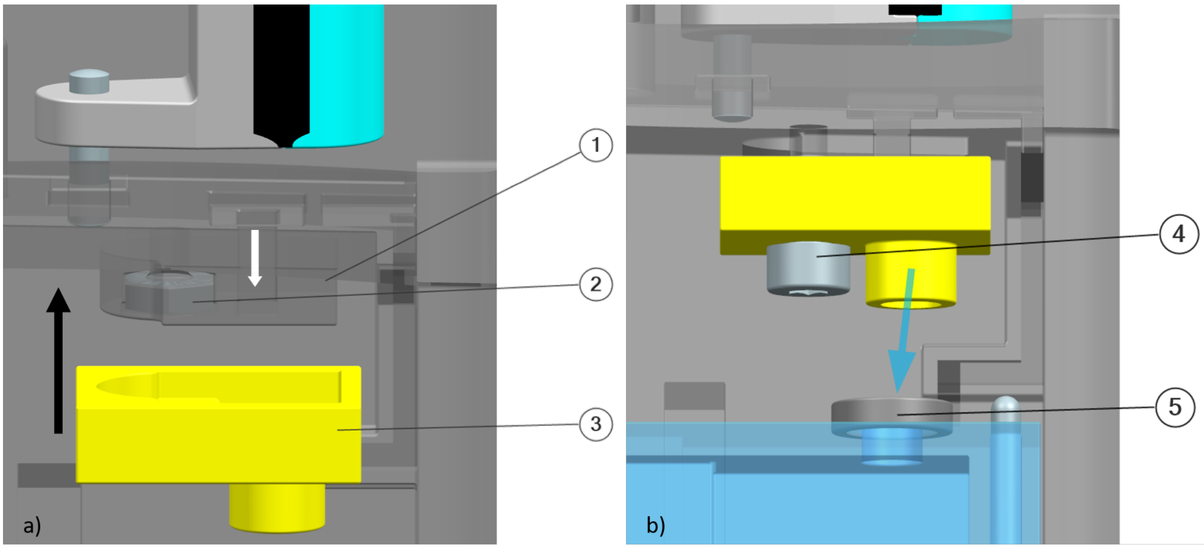


Figure 6.35 Filter Support Fixation

Having, by now, explained how the water reaches the filter, represented with the white arrow (Figure 6.35 a)), it is important to understand how to take it back to the water reservoir, considering that it is in good conditions to be used once more. This is guaranteed by removing the water reservoir cap and adding a connection tube to make the bridge between the end of the filter support and the reservoir entrance, numbered with a "five" in Figure 6.35 b).

After the general functioning of the prototype has been introduced, it is important to go into some details regarding the choice of two of the components. Thus, the specific analysis of the servomotor and water pump is made ahead. The datasheets of both components are attached in Appendix D.

Servomotor

The need to control the rotation of the wiper so that it could be leaning against the protection window, whenever the cleaning system is active, resulted into choosing a servomotor capable of performing this function.

A servomotor is a rotary actuator or linear actuator that allows for precise control of angular or linear position, velocity and acceleration. It consists of a suitable motor coupled to a sensor for position feedback [45]. Once more, the main concern falls upon the size and dimensions of the motor capable to perform what is asked.

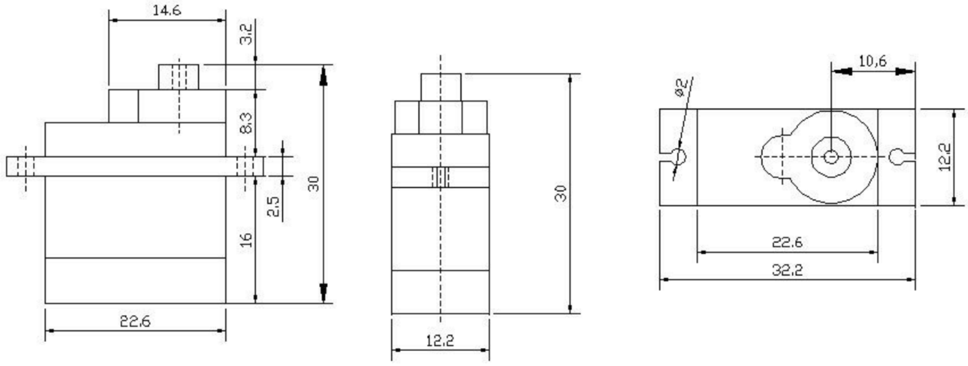


Figure 6.36 Servomotor dimensions

The servomotor controls the arm, where the wiper is mounted. Consequently, the wiper support rotates in solidarity with the arm. The amount of rotation is defined between the 'Zero position', not touching the protective window, and the 'On position', leaning against the protective window.

Table 6.3 Servomotor specifications

Operating Voltage	3.5 - 6V
Supply Voltage	4.8 - 6V
Torque	1.6kg/cm
Operating Temperature	-30 to +60ºC
Weight	9g
Dimensions	22.6 x 12.2 x 30mm

Water Pump

The first concern to chose the adequate water pump for the purpose is the *maximum head*. In other words, it is how much can the pump elevate the water or how far can the pump pressurise water against gravity. In this case, having, the LiDAR System, an average height of 200mm, and supposing that the water should rise from the bottom of the lateral support until the top, the chosen pump must have, at least, 200mm as the maximum head value. Another factor to consider are the pump dimensions. The pump must fit in the previous designed lateral support. Therefore and with all this considerations in mind the chosen pump is the following:

Table 6.4 Water Pump Specifications

Ports	2-Port Pumps
Input Voltage	6V
Current	0.07A
Power Usage	0.42W
Free Flow Rate	150 ml/min
Pressure Head	400mm
Weight	9g
Size	27x14x14 mm
Tubing bore size	2.4 mm
Noise	15 dba
Temperature Range	-20 to 120ºC
Max Pressure	1 bar =14.5 psi
Body	Anodised Aluminium

6.4 Concept Production

Known all the components involved in the design of the active cleaning system solution, the next step falls upon the production of the non-standard ones. In the present section the materials for each component will be introduced as, also, their fabrication process and surface finishing.

Table 6.5 Non-standard components description

Component	Resolution	Qtt	Material	Fabrication Process	Surface Finishing
Lateral Support	Layers 0.15mm	1	Accura25	SLA	Shot Blasting Painting
Plug-in socket	Layers 0.15mm	2	Accura25	SLA	Shot Blasting Painting
Water Reservoir	Layers 0.15mm	1	Accura25	SLA	Shot Blasting Painting
Filter Support	Layers 0.15mm	1	Accura25	SLA	Shot Blasting Painting
Nozzle Support		1	Aluminium[1]	Machining	
Arm Cover		1	Aluminium[1]	Machining	
Wiper Left Support		1	Aluminium[1]	Machining	
Wiper Right Support		1	Aluminium[1]	Machining	
Polimeric Cover	Layers 0.15mm	1	Accura25	SLA	Shot Blasting Painting
Reservoir Cap	Layers 0.15mm	1	Accura25	SLA	Shot Blasting Painting

Regarding the materials used in the components, a brief introduction of them both will be done. Thereby, the materials used are:

- **Accura25** - flexible plastic, ideal when high detail is required, while simulating the structural properties and aesthetics of ABS and Polypropylene. It is reliable and robust for functional prototypes. It is also the best resin available using the SLA technology.

[1]Aluminium Alloy EN AW 5083-H111

- **Aluminium Alloy EN AW 5083-H111** - is a medium strength, non heat-treatable alloy with excellent corrosion properties. This material will be used in the components where force will be applied, more precisely, the ones affected by the force from the protective window force against the wiper during the cleaning process and, also, in the rotation of the wiper.

The correspondent datasheet of each material, given by the parts suppliers, *SOLIDtech*, are attached in Appendix D. The Accura25 and Aluminium Alloy EN AW 5083-H111 mechanical properties are summarised in Table 6.6 and 6.7, respectively.

Table 6.6 Accura25 Mechanical Properties

Mechanical Properties	Value
Tensile Strenght	38 MPa
Tensile Modulus	1590-1660 MPa
Elongation at break	13-20%
Flexural Strenght	55-58 MPa
Flexural Modulus	1,38 - 1,66 MPa
Impact Strenght (Notched Izod)	19 - 24 J/m
Hardness, Shore D	80
Glass Transition (Tg)	60°C

Table 6.7 Aluminium Alloy EN AW 5083-H111 Mechanical Properties

Mechanical Properties	Value
Tensile Strenght	270 MPa
Tensile Modulus	70 MPa
Elongation at break	15%

In terms of the fabrication processes, the components made of Accura25 were obtained through SLA (stereolithography, a 3D printing process which has the ability to produce high-accuracy, isotropic, and watertight prototypes. It is, generally, the best process to obtain functional prototypes. SLA parts have the highest resolution and accuracy, the clearest details, and the smoothest surface finish of all the technologies available of 3D printing. That is the reason why it was used in this dissertation's prototype, considering the minimal details which needed to be manufactured. Another advantage of SLA is that when the printing happens at 'close to room' temperatures, they tend to not suffer from thermal expansion and contraction, which, for example, can happen during the

FDM (Fused Deposition Modeling) printing process [46] [47] [48]. Being this dissertation's project a prototype, it is not designed to be directly industrialised. Overall and in this case, the prototype works to observe how well a product matches the intended specifications. Manufacturing of functional prototypes using conventional methods, other than 3D Printing, is usually a time consuming procedure, which implicates being more expensive for small batch numbers. When producing a prototype, 3D printing reduce costs and the lead time required for the tooling phase and set up phases of processes like injection moulding, for instance. However, in the future, for industrialisation, 3D printing is too expensive to be considered and does not compete with the price of large-lot production [49].

Regarding the prototype part's surface finishing, it was used the process called *Shot Blasting*. This process intends to give a prior-preparation of the surfaces prior to further processing, in this case, the part's painting. It cleans the surface, adds texture to enhance paint adhesion and tend to increase the coating life [50] [51].

6.4.1 Assembly sequence

In this Section, the assembly scheme will be presented through prototype pictures

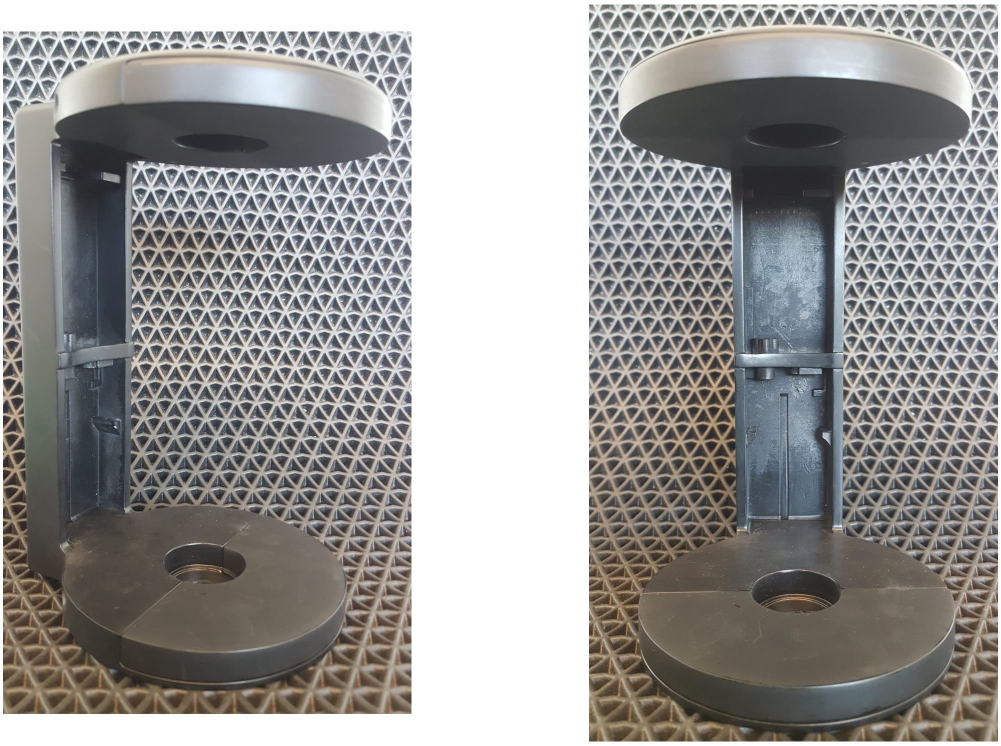


Figure 6.37 Lateral Support

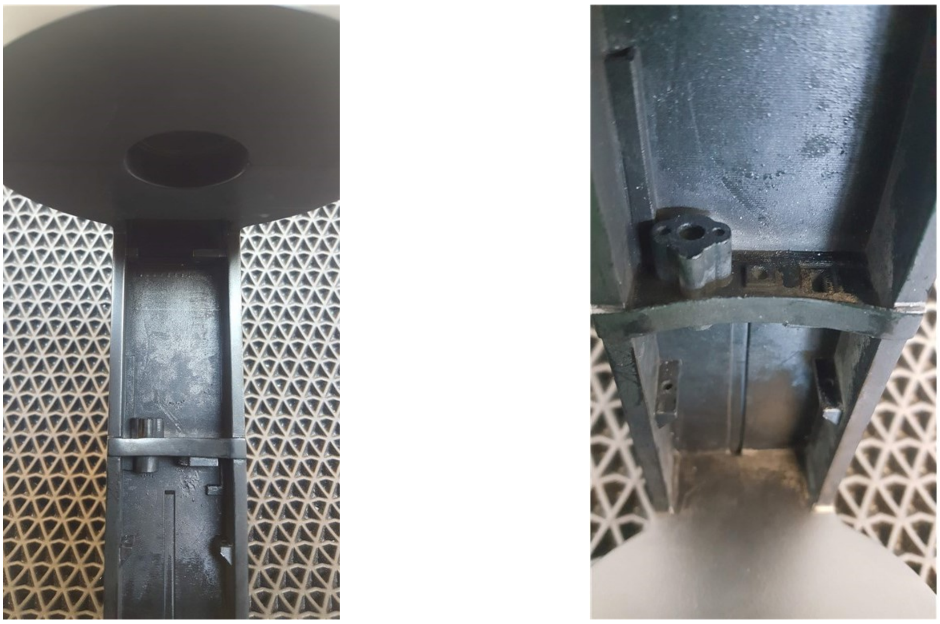


Figure 6.38 Lateral Support Details

Figure 6.40 Lateral Support Back View

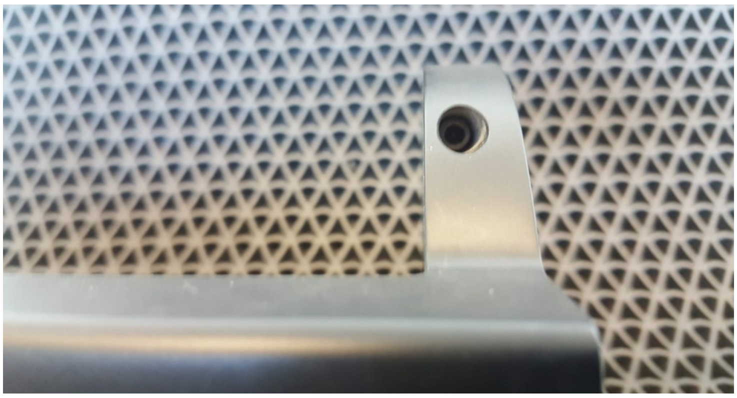


Figure 6.39 Insert detail

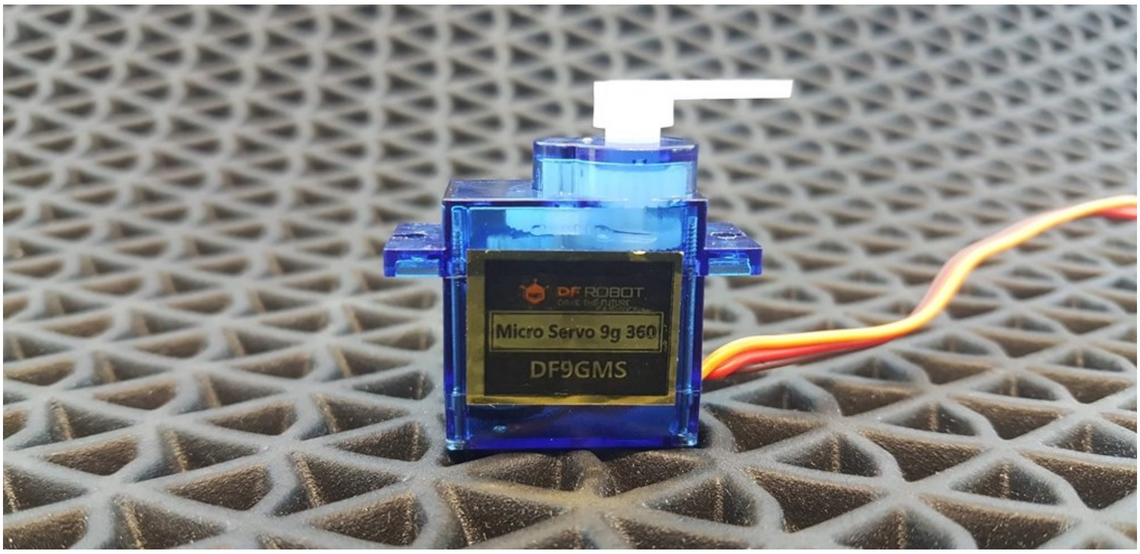


Figure 6.41 Servomotor for wiper rotation

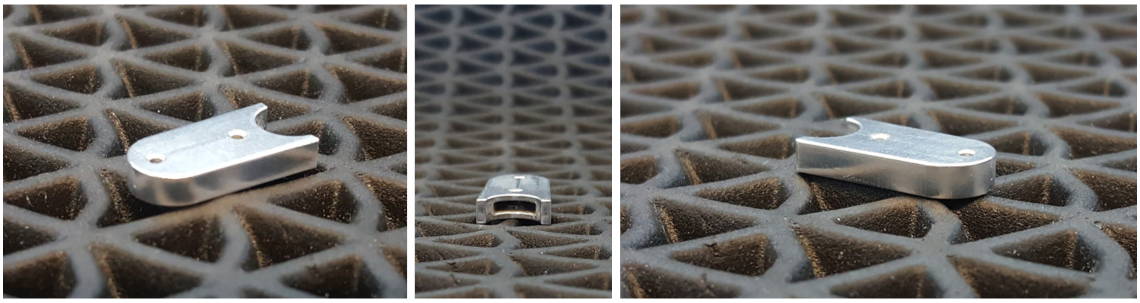


Figure 6.42 Arm Cover

Figure 6.43 Wiper Support Parts

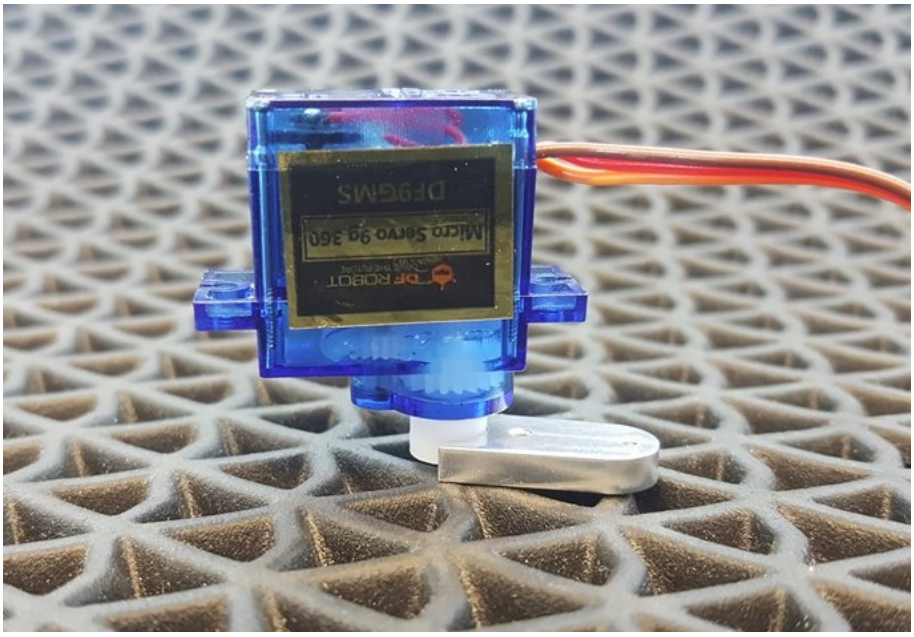


Figure 6.44 Servomotor and Arm Cover

Figure 6.45 Wiper Support Parts and Servomotor

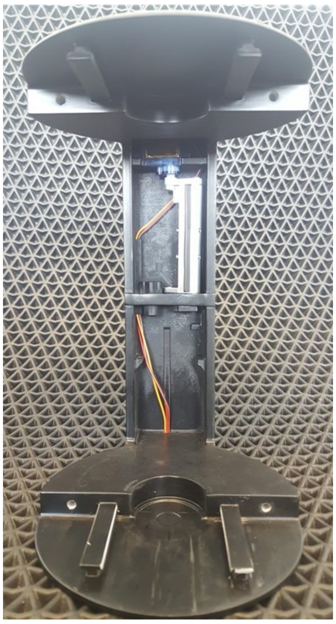


Figure 6.46 Prototype's Inside View

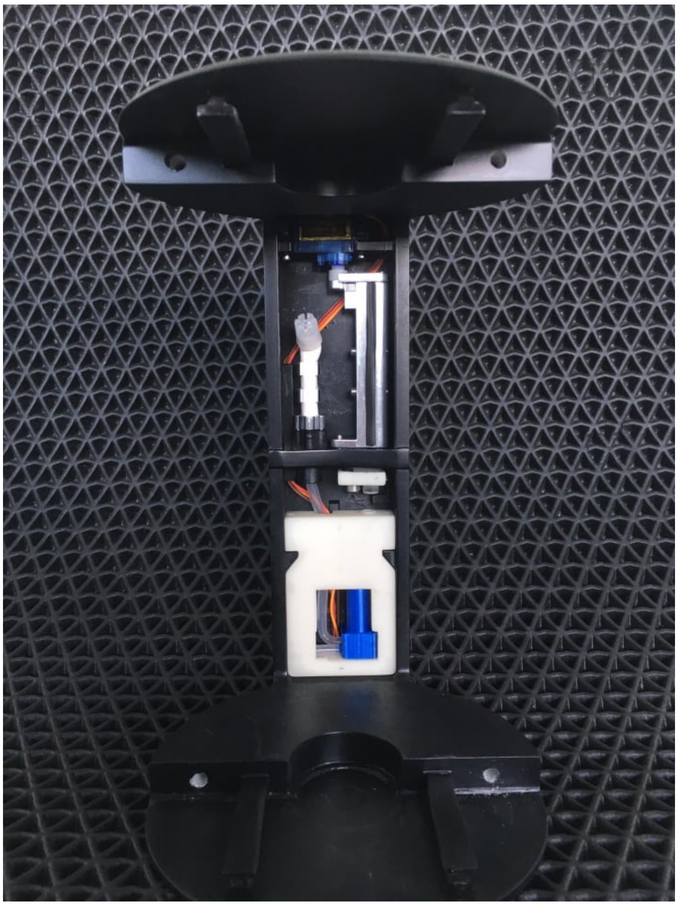


Figure 6.47 Cleaning System

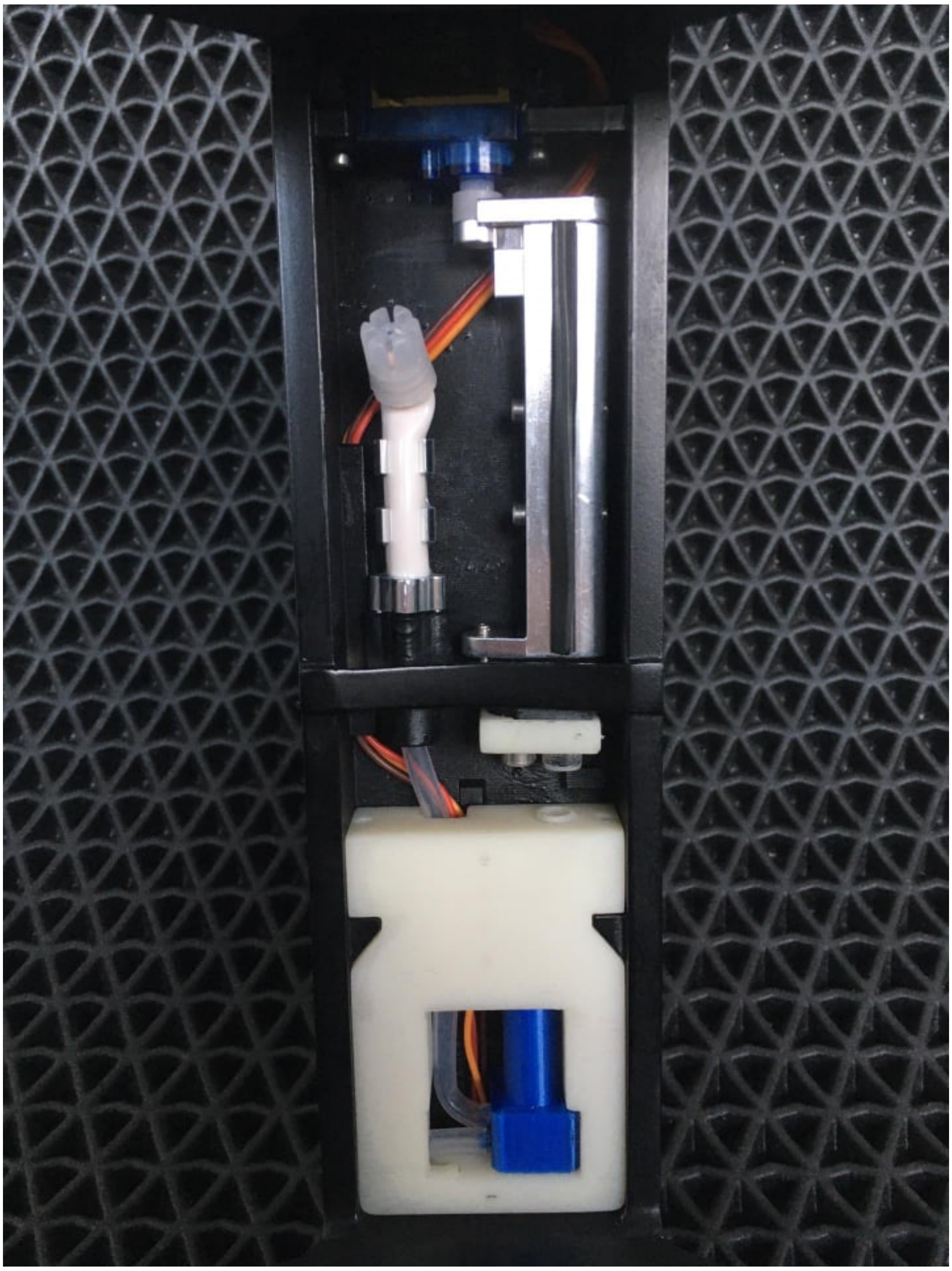


Figure 6.48 Cleaning System in detail

Figure 6.49 Final Prototype - POW next to the Cleaning System

Figure 6.50 Final Prototype

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Chapter 7

Prototype Testing

This chapter aims to provide the reader with information about the testing of the POW. The chapter begins with a introduction to materials chosen for testing, the explanation of the different tests, setups and results.

7.1 Protective Optical Window

In order to have the higher possible transmittance in the POW, its selection of the material for it is a critical step. Both optical and mechanical requirements are crucial to ensure that the LiDAR does not loose important visual information, whatever the pollution thrown at it. Hence, it is relevant to perform several tests to promising materials in order to choose the most appropriate, which will be applied to the POW of Bosch's LiDAR.

For the POW, the following characteristics are desired:

- High transmission for the desire wavelength (1550nm);
- High resistance to the shock;
- Low Coefficient of Thermal Expansion (preferably isotropic material);
- Low ageing effects and reliability;
- Hydro/super-hydrophobic.

The first test to perform will be a *Transmission Test*, but first, it is important to select materials to be used. The samples are requested from suppliers and have different properties, which will be detailed ahead. The results for each chosen material, based on the theoretical information gathered previously, in Section 3.6.1, will be also presented. The POW material will be selected in conformity with those results. It is important to recall Section 3.6.1, where it was concluded that, besides glass, the materials with a higher value of transmittance are Acrylic, TPX, NAS and Polycarbonate. Still relevant to emphasise is that typical glass used in common automotive applications is not applicable, because the IR radiation is absorbed by it. Thus, several materials were chosen to proceed with the transmission tests, and are presented in Table 7.1.

Table 7.1 Optical materials and features.

Name	Material	Features
Makrolon 2675	Polycarbonate	Coating AS4700
Makrolon 2407	Polycarbonate	Color code: 971000
PMMA Plexiglass	Polymethyl methacrylate/Acrylic glass	
CaF2	Calcium Fluoride	
Wideye 905	IR Glass	Transparent

From Table 7.2 to Table 7.5 are presented the relevant properties for each material from Table 7.1, except Wideye's because the information is not available.

Table 7.2 PMMA Plexiglas POQ62 Properties [52]

Properties	Value
Tensile Modulus	3300 MPa
CTE	70 μm/K
Resistivity	1x 10^{13} Ωm
Density	1190 kg/m^3
Refractive Index	1.49
Thermal Conductivity	0.21 W/m.K

Table 7.3 Makrolon 2407 971000 Properties [53]

Properties	Value
Tensile Modulus	2400 MPa
CTE	65 μm/K (isotropic)
Resistivity	1x 10^{15} Ωm
Density	1200 kg/m^3
Refractive Index	1.58
Thermal Conductivity	0.2 W/m.K

Table 7.4 Makrolon AX2675 Properties [54]

Properties	Value
Tensile Modulus	2400 MPa
CTE	65 μm/K (isotropic)
Resistivity	1x 10^{13} Ωm
Density	1200 kg/m^3
Refractive Index	1.58
Thermal Conductivity	0.2 W/m.K

Table 7.5 CaF2 Properties [55]

Properties	Value
Tensile Modulus	75.8 GPa
CTE	18.8565 μm/K (isotropic)
Density	3.18 kg/m^3
Refractive Index	1.4
Thermal Conductivity	9.71 W/m.K

7.1.1 Transmission Tests

To measure the transmission of each material, or more specifically, to quantify the amount of the light that travels through the POW without being reflected absorbed or scattered, the following setup was implemented, as seen in Figure 7.1.

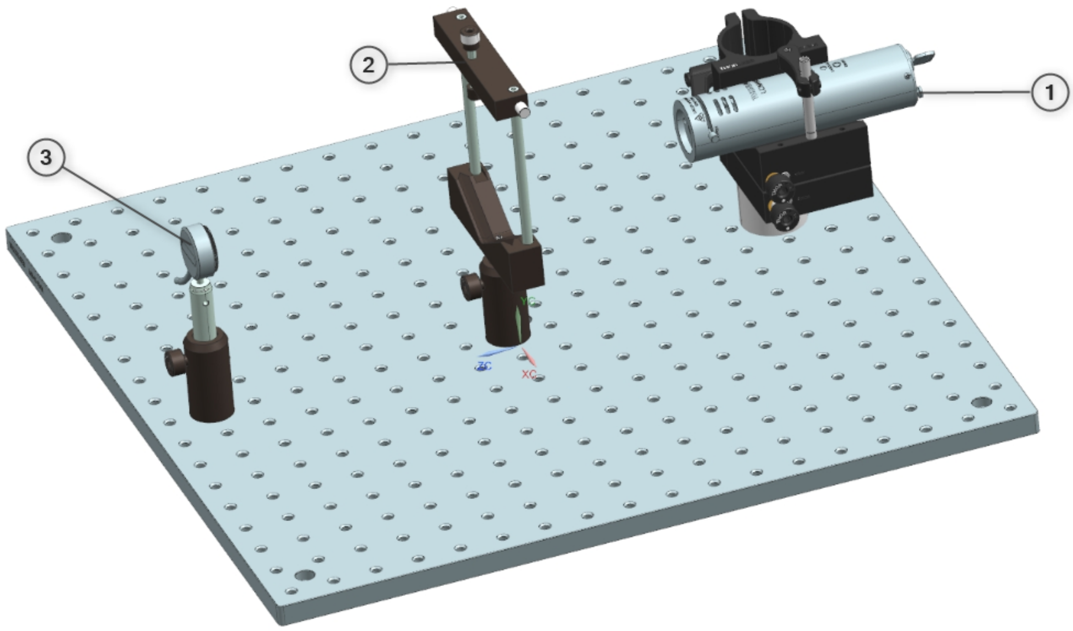

Figure 7.1 Transmission Test Setup (1) Light Emitter (Laser)@1550nm (2) Sample Holder (3) Powermeter

In order to implement this setup the following items are necessary:

- **Laser Diode Module 1550 laser Class 1 @1550nm** (x1) - Class-1 lasers are eye-safe in all operations even for a long time of exposure.
- **Sample Holder** (x1)
- **Photodiode Power Sensor - Powermeter** (x1)
- **Powermeter console** (x1)

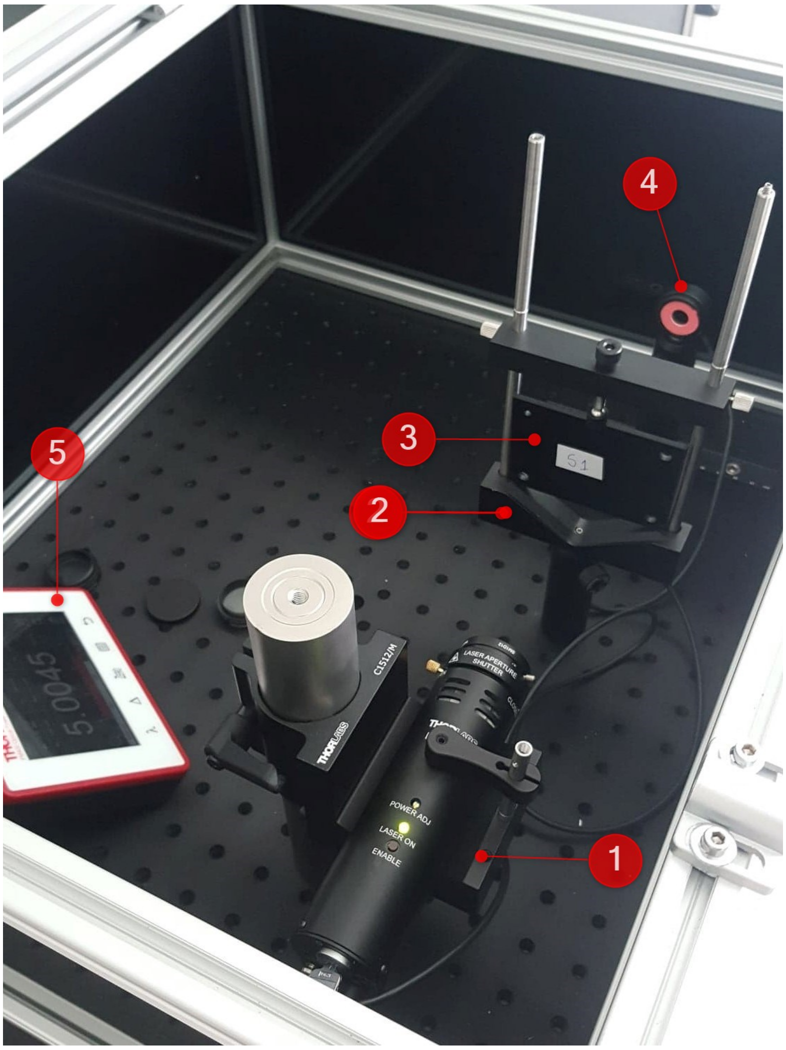

Figure 7.2 Transmission Test Setup

Figure 7.2 shows the actual setup of the transmission test. It is, also, possible to see the Powermeter console (#5), where the power that reaches the powermeter (#4) is shown.

In order to execute correctly the measurement, the crucial steps are:

- Mounting the sample (#3), as seen in Figure 7.2.
- Turn on the laser, the powermeter and align the refracted beam with the powermeter aperture, as seen in Figure 7.3. To perform the alignment, a detection card is needed, which, in this case, detects wavelengths from 400nm to 640nm and from 800nm to 1700nm.
- If the beam is coincident with the powermeter (#1), the transmitted power is shown in the powermeter console (#5).

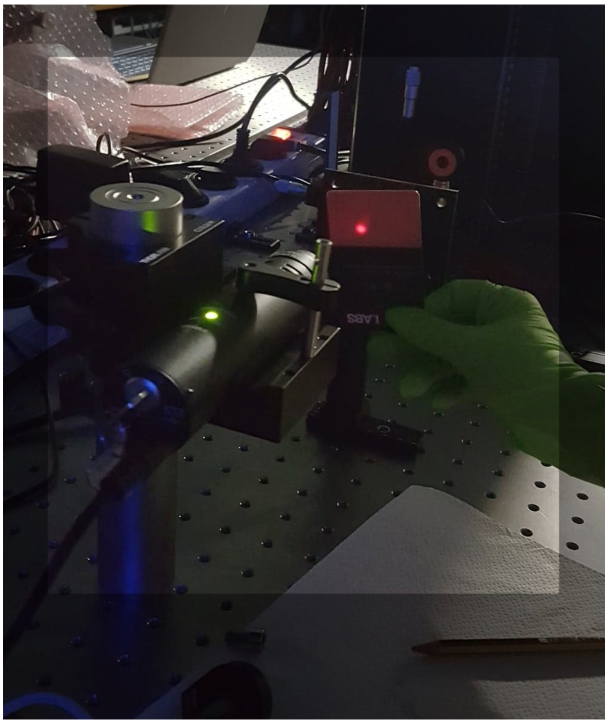

Figure 7.3 Beam Alignment

Concluding, at this point, the methodology explanation for the transmission test, the results will be presented further ahead.

In Table 3.6.1, in the second column is register the transmitted power from the Laser Source (W). Having, also, the values from the received power in the powermeter, registered in the third column and Being the transmittance calculated as show in equation , it is possible to calculate the percentage of light that, effectively, passes through the POW, to the outer side of it

$$Transmittance = \frac{I}{I_0} \times 100 \ (\%) \tag{7.1}$$

.

Where I represents the power received in the powermeter and I_0 the power emitted from the source.

Table 7.6 Optical materials and transmittance.

Material	Emitted Power (W)	Received Power (W)	Transmittance (%)
Makrolon AX2675	35.7	30.7	86
Makrolon 2407	35.7	30.9	87
PMMA Plexiglass	35.7	30.8	86
Calcium Floride, CaF_2	35.7	33.4	94
Wideye905	35.7	19.6	0.55

The results of the test indicate:

- CaF_2 glass presents the highest transmission value for the tested wavelength, 1550nm;
- Wideye905 presents a low value of transmittance, compared to the overall results, due to the filter and anti-reflection coating which was optimised for 905nm and not for the tested wavelength;
- All the polymers present similar transmission values for the tested wavelength.

From the results, at first sight, the most suitable material would be CaF_2, however the lack of good thermal conductivity and fragility makes it undesirable [56] for the fabrication of the POW.

Thereby, next best result after, CaF_2, is *Makrolon* 2407, which is a UV stabilized polycarbonate and presents low viscosity. It exhibits easy release, high heat resistance, good toughness and good electrical insulation properties and provides durability,

Wideye 905 was taken out of the equation, based on the transmittance values. As future work, it would be interesting to test the Wideye but for the laser wavelenght, 1550nm.

Comparing, PMMA Plexiglass (Acrylic) and Makrolon (Polycarbonate), the following topics were crucial for the decision:

- Polycarbonate has a higher chemical resistance than acrylic;
- Polycarbonate is a durable material. It has high impact-resistance [57] [58] [56], what makes it appropriate for LiDAR applications, where pollution might stick to it at high velocities.

Taking all the previous considerations into account, the material with which the next tests will be performed is *Makrolon* 2407.

In Section 7.1.2, several samples of the chosen material, *Makrolon* 2407, were submitted to an *Pollution and Aerodynamic Test*. This test was performed at INEGI, in the wind tunnel, and its purpose was to observe the aerodynamic influence in a polluted POW, simulating a car driving in a highway.

7.1.2 Aerodynamic influence in pollution - INEGI tests

This test was performed at INEGI's Aerodynamic and Calibration Laboratory. The wind tunnel is fitted with a standard port for stack sampling laboratories.

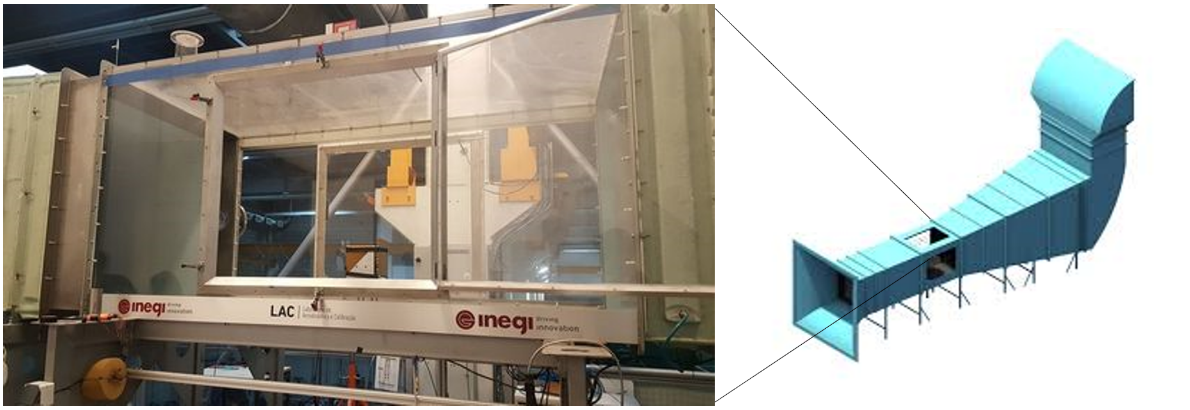

Figure 7.4 Wind Tunnel - INEGI's Aerodynamic and Calibration Laboratory

These tests were performed with 3 different types of pollutants:

- Yogurt - to simulate biogenic material;
- Arizona Dust
- Salty water

The samples were mounted in a previous Bosch's prototype, as seen in Figure 7.5.

Figure 7.5 Samples for testing

Table 7.7 Samples for testing - Aerodynamic influence in pollution

	With rotation	**Without rotation**
Arizona Dust	Sample 2	Sample 1
Salty Water	Sample 4	Sample 3
Yogurt	Sample 6	Sample 5

In the prototype, seen in Figure 7.5, the cleaning method to clean the samples is its rotation, creating a centrifugal force. In Table 7.7 the samples tested are divided in two categories: with rotation and without rotation.

In this work, the relevant results are the ones without rotation, because, even though there is a rotation in the 'Rotating Housing' concept, it is not in the same axis as the rotation of the previous figure concept. Thereby, we can not assume that the results might be comparable.

Thus, the principal results to focus on are the ones from the column 'No rotation'. In this case, the sample is fixed in the prototype, and the velocity of the wind in the tunnel is, approximately, $97km/h$. This situation simulates a car driving in a highway at the mentioned velocity.

To add the pollution to the samples inside the wind tunnel, after the stabilisation of the wind velocity, at the desirable 97km/h, the pollutants were thrown at the sample with a sprayer. This step of the test can be seen in Figure 7.6.

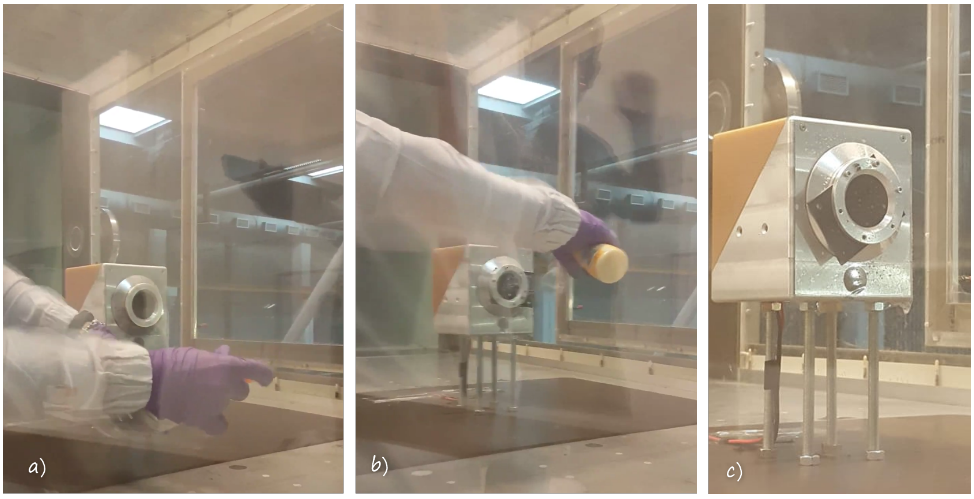

Figure 7.6 Polluted samples inside the wind tunnel a) Sprayer b) Yogurt c) Sample fixed in the prototype

After being polluted, the samples were submitted to a transmission test, to evaluate the influence of the pollution in the transmission of the POW and, also, to a Water Contact Angle Test. However, in the next Section , which shows the transmission of each sample, after the tests performed at INEGI, will be studied the impact of the pollution and aerodynamic factor in the transmission.

7.1.3 Transmittance after pollution Test

In this Section the transmittance after the pollution and aerodynamic tests will be measured.

The already obtained value for the transmittance in a clean sample of *Makrolon* 2407 is 87%, calculated in Section 7.1.1. The remainig values were obtained using the same principles and steps as in Section 7.1.1.

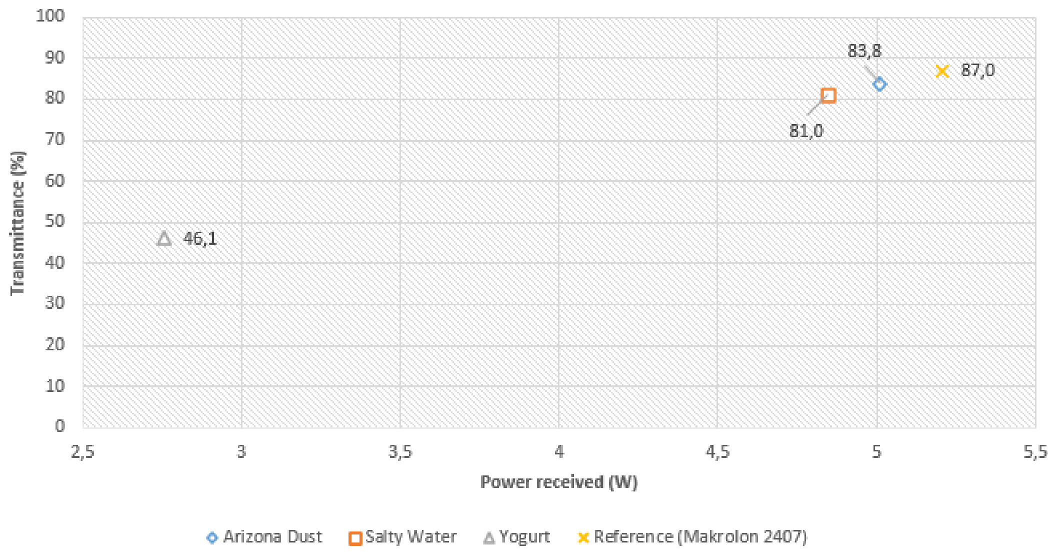

Figure 7.7 Transmission of polluted samples

With this graphic, it is possible to conclude that:

- All the 3 pollutants interfere with the transmittance value registered in the sample;
- Yogurt is the pollutant with higher impact in the POW, with the transmittance being reduced approximately 41%.;
- Arizona dust is the pollutant which less contributes to the decrease of transmittance, followed by Salty Water.

The last test to be performed will be the *Water Contact Angle* Test, in Section 7.1.4.

7.1.4 Water Contact Angle vs Pollution Test

The contact angle with water is the angle that the surface of a liquid forms when it comes in contact with a solid. It is one of the common ways to measure the wettability of a surface or material. Wetting refers to the study of how a liquid deposited on a solid (or liquid) substrate spreads out or the ability of liquids to form boundary surfaces with solid states. The value of the water contact angle depends mainly on the relationship that exists between the substract and the liquid, specially the cohesive forces between them. When the angle of contact with water of a given material is less than 90º, it is said that this material is hydrophilic, when it is between 90º and 150º, it is said that the material is hydrophobic and when it is greater than 150º, material is already considered super-hydrophobic [59] [60]. The previous explanation is schematised in Figure 7.8.

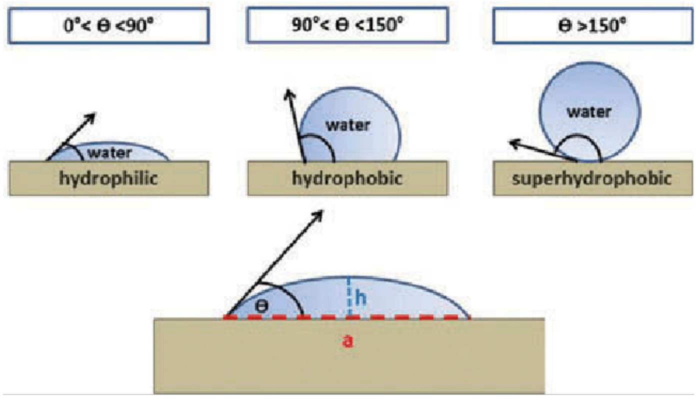

Figure 7.8 Definition of surface properties in contact with liquids [60]

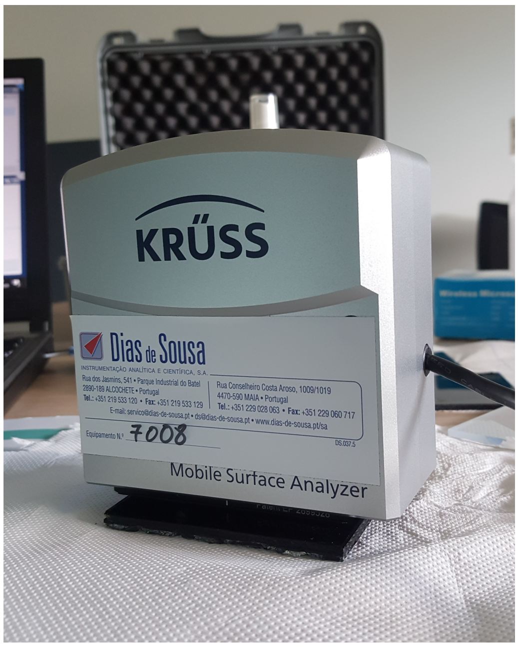

Figure 7.9 Device - Mobile Surface Analizer

The angle of contact with water for each material sample was measured by calculating the right and left tangent to the surface of the 2D image, using a device called the Mobile Surface Analyzer, shown in Figure 7.9. After pressing a button, and placing the sample in the bottom of the device, a small drop of approximately 5-6μL is released to the sample.

The calculation of the water contact angle for each material was based on Young's equation, which is as follows:

$$\gamma_{SG} - \gamma_{SL} - \gamma_{LG}\cos\theta_c = 0$$

γ_{SG}: Solig-Gas Surface Energy

γ_{SL}: Solig-Liquid Surface Energy

γ_{LG}: Liquid-Gas Surface Energy

θ_c: Water contact angle

Ahead in this Section, it will be presented the Water Contact Angle results for each sample, which means that will be possible to analyse if the pollutants affect the adhesion of liquids to the tested material.

The following Figure is considered as Reference. The graphic illustrates the variation of the water contact angle for the sample of *Makrolon* 2407 without being polluted. This Reference will, later on, be compared to the other polluted samples.

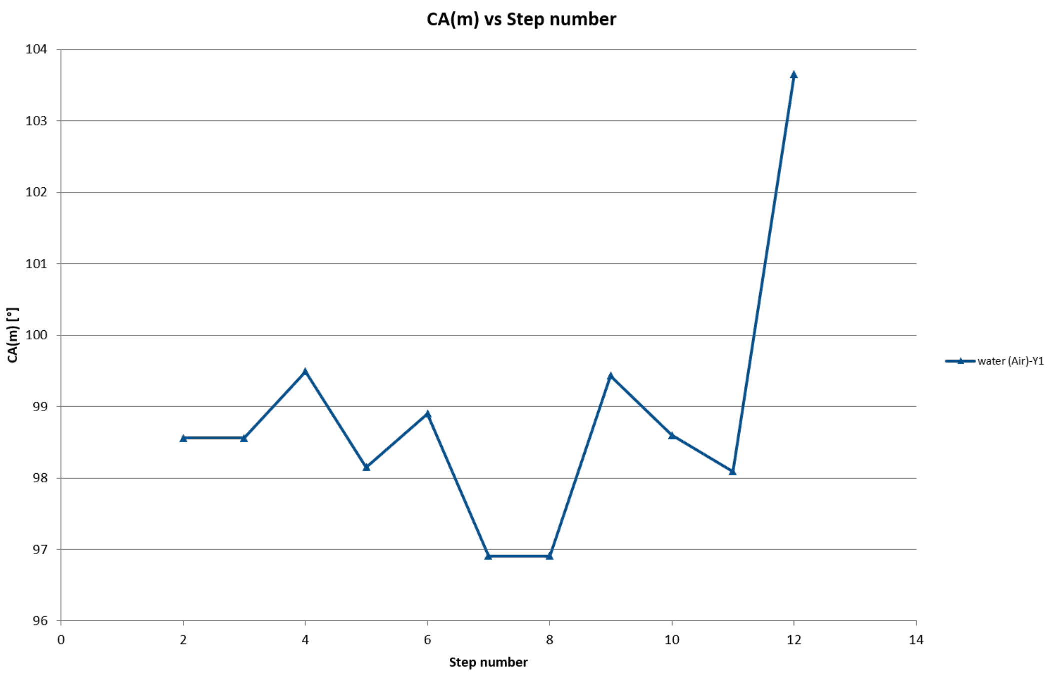

Figure 7.10 Reference Sample - *Makrolon* 2407 without pollution

In the next one, it is presented the same graphic for Sample 1, where the pollutant is arizona dust.

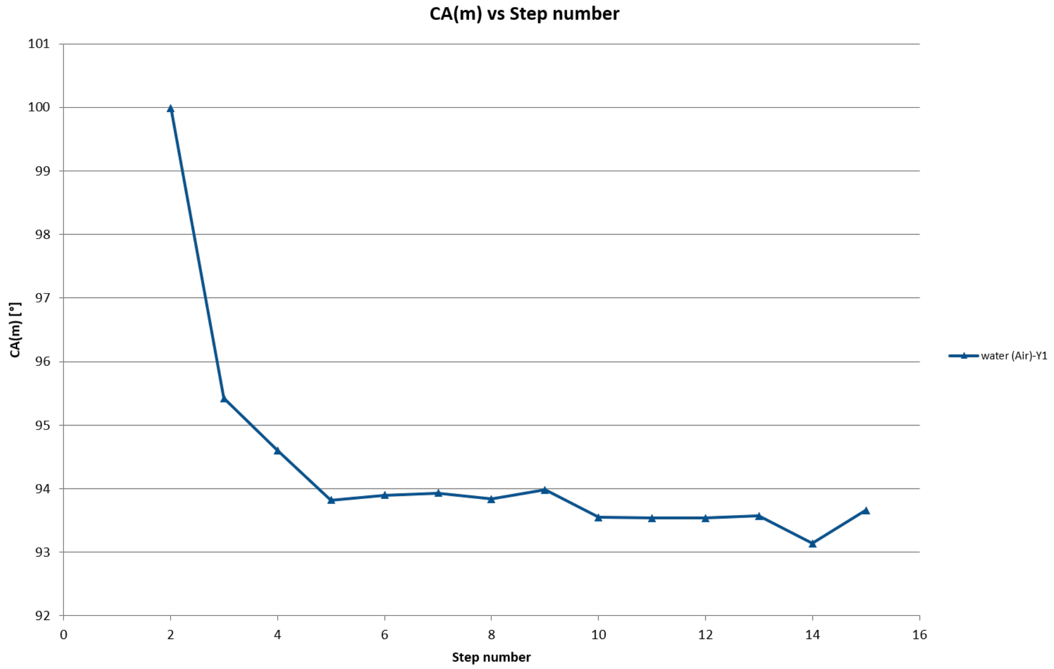

Figure 7.11 Contact Angle Sample 1 - *Makrolon* 2407 Arizona Dust

In the following figure, it is presented Sample 1, polluted with Arizona Dust, after the water drop to analyse being released.

Figure 7.12 Sample 1 - Makrolon2407 Arizona Dust

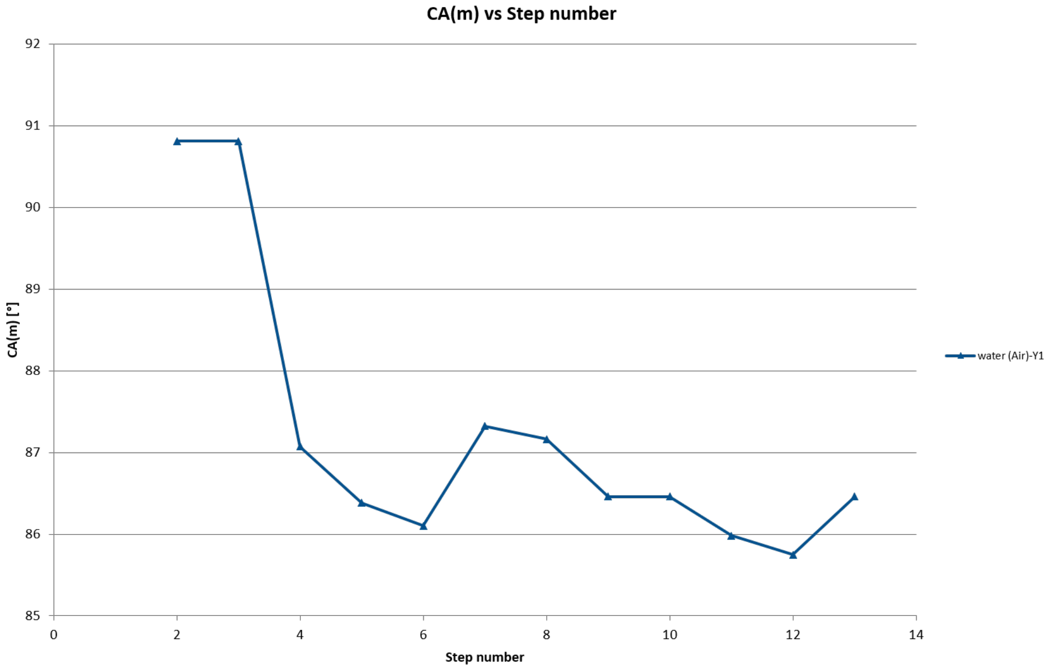

Figure 7.13 Contact Angle Sample 3 - *Makrolon* 2407 Salty Water

In the previous figure is presented the graphic with the contact angle in each step, which means, all the measures taken by the device. In the following, Sample 3 is shown, polluted with salty water, after the WCA test.

Figure 7.14 Sample 3 - *Makrolon* 2407 Salty Water

Finally, the last sample is Sample 5, polluted with yogurt, to simulate the consistency of biogenic material. Firstly, the graphic with the contact angle is shown and then the drop itself.

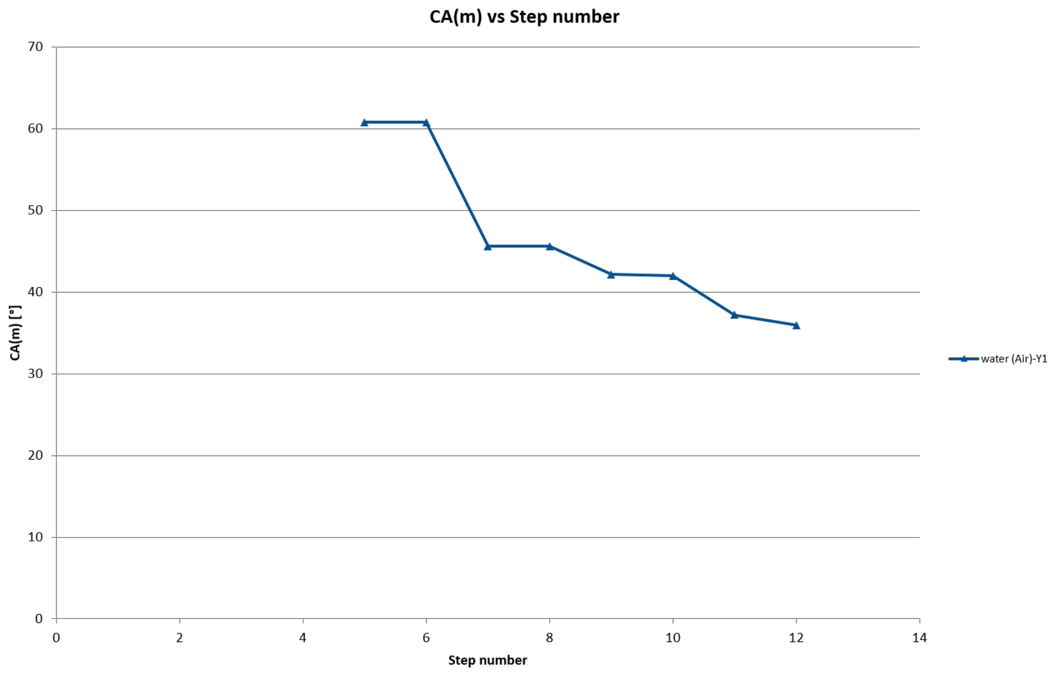

Figure 7.15 Contact Angle Sample 5 - *Makrolon* 2407 Yogurt

Figure 7.16 Sample 5 - *Makrolon* 2407 Yogurt

In Table 7.8, is presented, for each sample and pollutant, the average Contact Angle.

Table 7.8 Samples Contact angle

	Pollutant	**CA(m) [°]**
Reference		98,84
Sample 1	Arizona Dust	94,32
Sample 3	Salty Water	87,23
Sample 5	Yogurt	46,24

With the previous table it is possible to conclude that:

- The reference sample of *Makrolon* 2407 has the highest CA;
- Being the reference average contact angle of 98.84°, it is possible to conclude that the Polycarbonate *Makrolon 2407* is a hydrophobic material;
- All the pollutants decrease the contact angle, making the sample less hydrophobic;
- The pollutant which decreases drastically the hydrophobicity is yogurt;
- It is important to clean the sample, in this case, the POW, to reestablish the previous hydrophobic conditions.

7.2 Prototype CAD modifications

After the manufacturing of all the components and their assembly, it was perceivable that the actual assembly would be eased with the implementation of some details in the design of the prototype.

The design alterations to implement are:

- The design of a slot for the washers, which guarantees the fixation of the servomotor. These washers are hard to assembly because there is not enough space to immobilise them to proceed with the fixation.
- Create a passage for the servomotor cables to pass from the top of the prototype, where the servomotor is installed, to the bottom of that same level, without interfere with the wiper support.
- Design a diagonal path for the cables to pass from the interior of the lateral support to the exterior of the prototype.

Chapter 8

Conclusions and Future Work

The purpose of this dissertation was the development of a cleaning solution for the LiDAR sensor, more precisely, the integration of it in a concept by Bosch, called *Rotating Housing*. The analysis and results of the thesis end up in the manufacturing of a prototype with both, a passive cleaning system (POW material) and an active one. All of the previous was thought taken into account mechanical, optical, electronic and automotive requirements.

There is considerable uncertainty concerning autonomous vehicles development, benefits, costs and consumer demand, however considerable progress is being made.

That being said, in this Chapter, the main conclusions taken are complied in Section 8.1 and suggestions for future works are in Section 8.2.

8.1 Main Conclusions

With regard to the *Concept Development* phase it was concluded that:

- A thorough analysis of each component is crucial before the production phase to avoid possible errors;
- For a functional prototype or product, it is essential to pay attention to the tolerances asked to the manufacturer. The level of performance and the overall functioning of the prototype may depend on them, however, a balance between precision vs cost needs to be taken into account;
- It is important to define the tolerances, and the degree of deviation, to facilitate the reduction of manufacturing costs, without the prototype's functionality sacrifice.

Regarding the *Prototype Production* phase it was concluded that:

- The manufacturing of 3D printed prototypes and the investigation of their performance indicate that it is possible to produce a functioning prototype in the material Accura25;

- The major advantage of 3D printing was found to be the improved design possibilities and the manufacturing of complicated geometries while allowing for drastic reductions in weight;

- An aluminium alloy was also used to manufacture the components where a load would be applied. In this case, the wiper support components.

Regarding CAD modifications it was concluded that:

- After the manufacturing of all the components and their assembly, it was perceivable that the actual assembly would be eased with the implementation of some details in the design of the prototype;

- This modifications, without major alterations to the structure of the prototype,would allow the reduction of the assembly time and decrease its difficulty of assembly.

With respect to the experimental phase of this dissertation, the conclusions are:

- For the POW material selection, a balance between the optical and mechanical properties is crucial;

- The polycarbonate, Makrolon 2407, allowed the coexistence of them both, comparing, for example, with Acrylic, which presents the optical transmittance desired but lacks on good mechanical properties;

- Pollution affects the POW transmission, specially the yogurt, used to simulate biogenic material, with a percentage of loss of 41% face to the reference, without being polluted;

- Even with hydrophobicity properties, the POW needs an active cleaning system to reestablish the desirable transmission conditions.

- All types of pollution tend to affect the hydrophobicity of the Makrolon 2407, however, in different degrees.

- Being the reference average contact angle of 98.84°, it is possible to conclude that the Polycarbonate Makrolon 2407 is a hydrophobic material;

- The Makrolon's hydrophobicity decreases with all the pollutants. However the decrease with yogurt is the most significant one (52.6%);

- Salty water and Arizona dust also decrease the hydrophobicity of the sample, however, in a much smaller percentage: 11.61% and 4.52%, respectively.

8.2 Future Work

After the developing the active and passive solution and with an overall perspective of all the work developed, it is of interest to define some points to work upon in the future. In particular, some suggestions are:

- Having the possibility to increase in 30° the amplitude of the Lateral Support, from 60° to 90°, study the possibility to adapt the active solution for a wider Lateral Support and reduce the prototype's height;
- Study the increase of stiffness of the Lateral Support with a increase in its amplitude, from 60° to 90°, ;
- Testing the effectiveness of the active cleaning solution developed in this dissertation;
- Study the implementation of several liquids in the water reservoir to ease the cleaning process;

Finally, it would be of interest to study how to adapt the prototype developed for an industrialisation process.

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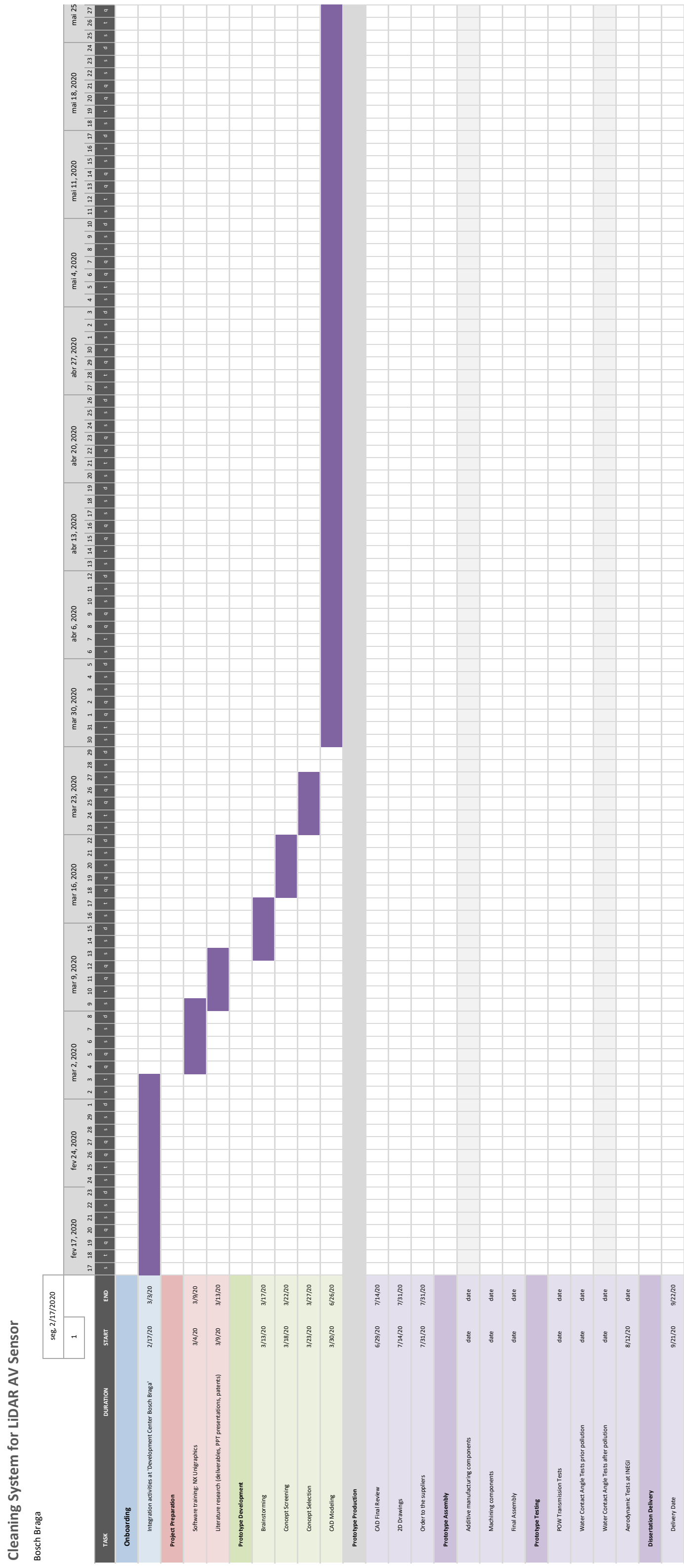
Appendices

Appendix A

Gantt Chart


Cleaning System for LiDAR AV Sensor
Bosch Braga
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TASK
DURATION
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Onboarding
Integration activities at 'Development Center Bosch Braga' 2/17/20 3/3/20
Project Preparation
Software training: NX Unigraphics 3/4/20 3/9/20
Literature research (deliverables, PPT presentations, patents) 3/9/20 3/13/20
Prototype Development
Brainstorming 3/13/20 3/17/20
Concept Screening 3/18/20 3/22/20
Concept Selection 3/23/20 3/27/20
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CAD Final Review 6/29/20 7/14/20
2D Drawings 7/14/20 7/31/20
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Machining components date date
Final Assembly date date
Prototype Testing
POW Transmission Tests date date
Water Contact Angle Tests prior pollution date date
Water Contact Angle Tests after pollution date date
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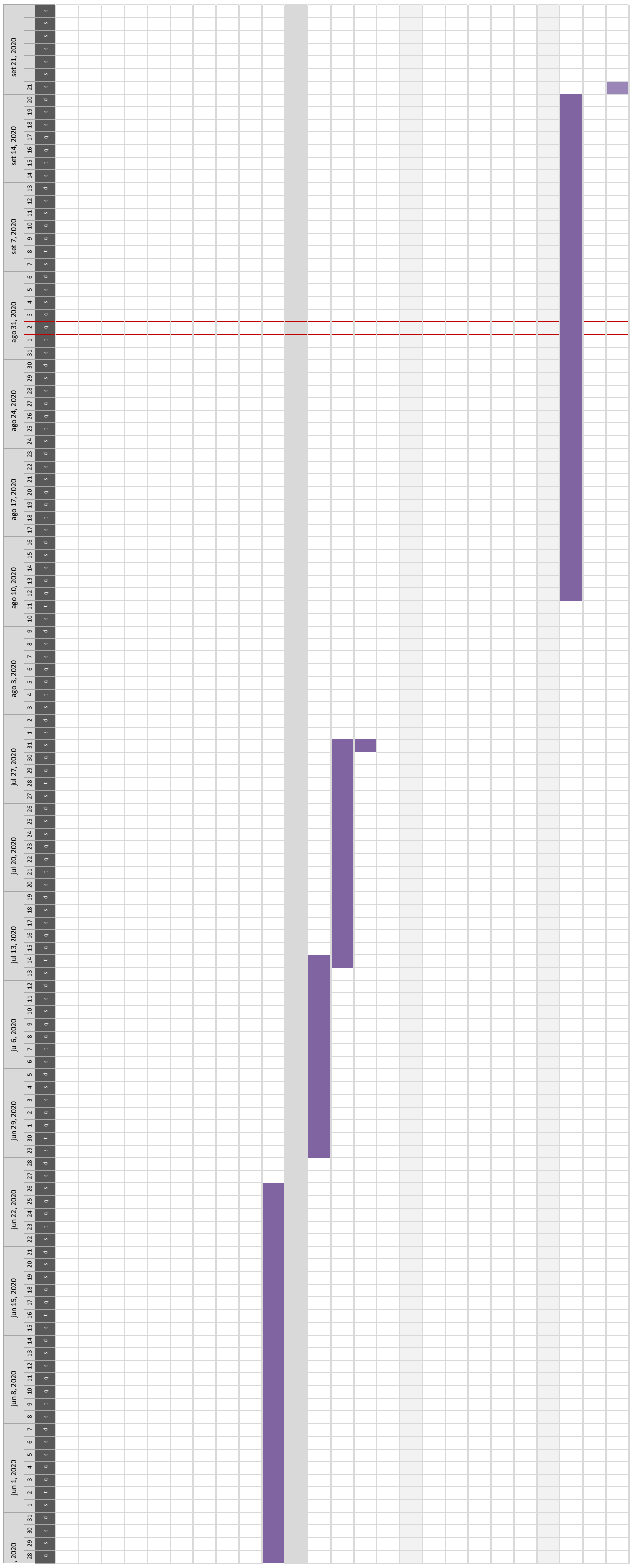
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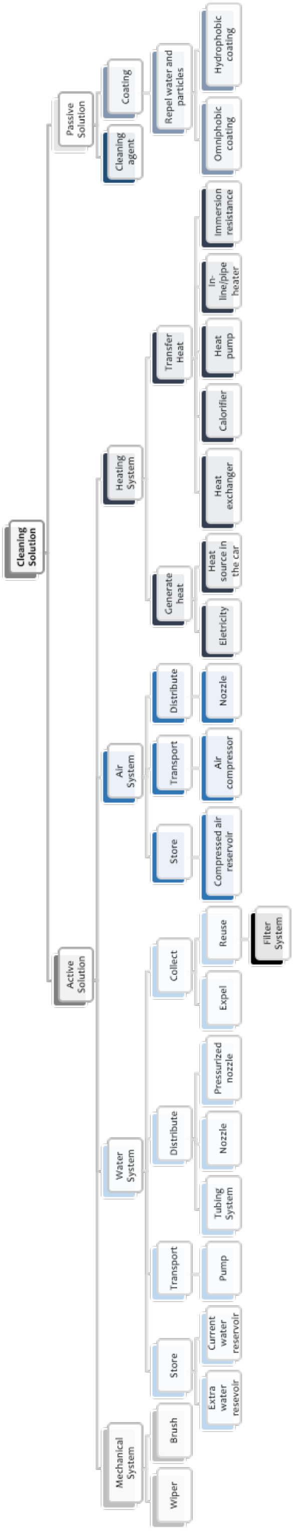
Appendix B

Matrix Decisions

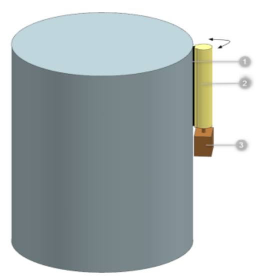
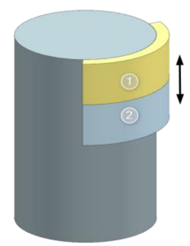
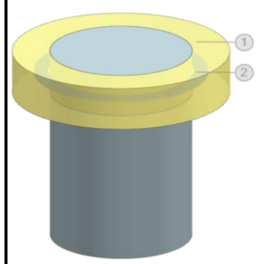
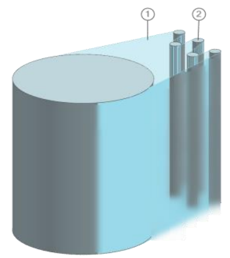
B.1 Functional Mapping


Cleaning Solution
Active Solution
Passive Solution
Mechanical System
Wiper
Brush
Water System
Store
Extra water resevoir
Current water reservoir
Transport
Pump
Distribute
Tubing System
Nozzle
Pressurized nozzle
Collect
Expel
Reuse
Filter System
Air System
Store
Compressed air reservoir
Transport
Air compressor
Distribute
Nozzle
Heating System
Generate heat
Eletricity
Heat source in the car
Transfer Heat
Heat exchanger
Calorifier
Heat pump
In-line/pipe heater
Immersion resistance
Cleaning agent
Coating
Repel water and particles
Omniphobic coating
Hydrophobic coating

Appendix C

Pugh Matrix

Evaluation of beneficial variants

	Reference	Variant 1	Variant 2	Variant 3
				

No.	criteria	weight factor G	Score B	Reason	G x B	Score B	Reason	G x B	Score B	Reason	G x B	Score B	Reason	G x B
1	Ease of integration into Bosch LiDAR concept	16,1	0	reference	0,0	-1		-16,1	-1		-16,1	0		0,0
2	Box volume fulfillment (including interface/mounting components)	17,9	0	reference	0,0	-1		-17,9	-1		-17,9	-1		-17,9
3	Lenght of cleaning process	7,1	0	reference	0,0	-1		-7,1	0		0,0	0		0,0
4	Risk of damaging the POW	25,0	0	reference	0,0	0		0,0	0		0,0	-1		-25,0
5	Assembly and instalation	5,4	0	reference	0,0	-1		-5,4	0		0,0	1		5,4
6	Possibility to perform its function at the same time as the cleaning	8,9	0	reference	0,0	-1		-8,9	0		0,0	1		8,9
7	Resources used (heat, water, others)	1,8	0	reference	0,0	-1		-1,8	0		0,0	-1		-1,8
8	Possibility of polution re emerging	17,9	0	reference	0,0	0		0,0	0		0,0	-1		-17,9
	sum	100,0		overall score:	0,0		overall score:	-0,57		overall score:	-0,34		overall score:	-0,48

Figure C.1 Evaluation of beneficial variants

Pugh-Matrix

Cleaning System for Bosch LiDAR

Evaluation of weighting factors

Scoring for pairwise comparison of criteria:

2	Red criterion more important than blue criterion
1	Red criterion has same importance as blue criterion
0	Red criterion less important than blue criterion

No.:	Criterion	1 Ease of integration into LiDAR concept	2 Box volume fulfillment	3 Lenght of cleaning process	4 Risk of damaging the POW	5 Assembly and instalation	6 Possibility to work at the same time as the cleaning	7 Resources used (Heat, water, others)	8 Possibility of polution re emerging	Sum	weight(%)	Rank
1	Ease of integration into Bosch LiDAR concept		0	2	0	2	2	2	1	9	16,1	4
2	Box volume fulfillment (including interface/mounting components)	2		2	0	1	2	2	1	10	17,9	2
3	Lenght of cleaning process	0	0		0	1	1	2	0	4	7,1	6
4	Risk of damaging the POW	2	2	2		2	2	2	2	14	25,0	1
5	Assembly and instalation	0	1	1	0		0	1	0	3	5,4	7
6	Possibility to perform its function at the same time as the cleaning	0	0	1	0	2		2	0	5	8,9	5
7	Resources used (heat, water, others)	0	0	0	0	1	0		0	1	1,8	8
8	Possibility of polution re emerging	1	1	2	0	2	2	2		10	17,9	2
										56	100,0	

Figure C.2 Evaluation of weighting factors

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Appendix D

Datasheets

D.1 Servomotor datasheet

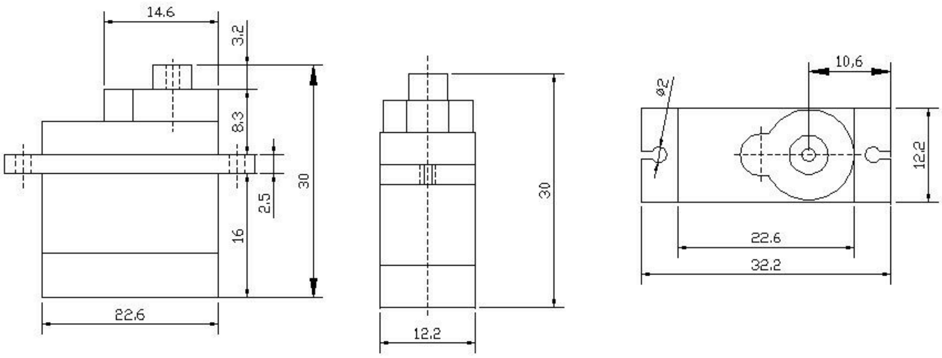
DFROBOT
DRIVE THE FUTURE

DFRobot DF9GMS 360 Degree Micro Servo (1.6Kg)
SKU:SER0043

INTRODUCTION

The DFRobot DF9GMS is a 360 degree micro servo. It uses a plastic gear drive and is light and compact. It can be used for various applications and DIY products, such as toy cars, boats, windmills etc.

A 360 degree servo's operation is more similar to a DC motor than a standard servo as only rotation direction and speed can be controlled. There is also no hardware stop inside so that the shaft can rotate freely. Compared to an ordinary DC motor, a 360-degree servo motor does not require additional motor drivers and is plug and play, compact and convenient. Arduino control methods are also the same. When the servo is operating on the 4.8 ~ 6V power supply, the torque can reach 1.2 ~ 1.6Kg x cm



SPECIFICATION

- Operating Voltage: 3.5 - 6.0V
- Supply Voltage: 4.8V ~ 6.0V
- Dead Zone Width: 5usec
- Working Speed: 0.12sec/60 (4.8V no load)
- Stall Torque: 1.2kg/cm (4.8V), 1.6kg/cm (6.0V)
- Neutral Location: 1500us
- Interface Description:
- Brown: GND
- Red: VCC
- Orange: S
- Cable Length: 250mm
- Operating Temperature: -30°C to + 60°C
- Dimensions: 22.6 x 12.2 x 30 mm /0.89x0.48x1.18”
- Weight: 9±1g

D.2 Water Pump datasheet

ENGLISH

Datasheet

Direct Coupling Centrifugal Pump, 150mL/min, 6 V

RS Stock number 480-184

Description

RS Miniature Pumps
High quality miniature pumps, ideal for the electronics (cooling), medical or aeronautical industries, and research & development of portable equipment. RS miniature pumps use the centrifugal principle and give a smooth pulseless flow. They are exceptionally quiet and reliable.

Specifications

Ports:	2-Port Pumps
Input Voltage (V):	6.0
Current (A):	0.07
Power Usage (W):	0.42
Free Flow Rate (ml/min):	150
Pressure Head (mm):	400
Weight:	9g
Size:	27x14x14mm
Tubing Bore Size (mm):	2.4
Maximum Viscosity (cSt):	20
Noise (dba):	15
IP Rating:	IP64
Temperature Range:	-20 to +120°C
Max Pressure (Bar):	1.0
Body:	Anodised Aluminium
Connectors:	Stainless Steel 316
Impeller:	Acetal
Seals:	Viton

D.3 Accura25 datasheet

STEREOLITHOGRAPHY

Accura® 25 Plastic

3DSYSTEMS™

Accura® 25 Plastic produces durable prototypes that are ideally suited for automotive design verification and functional testing.

Simulate the properties and aesthetics of polypropylene and ABS with this accurate and flexible material.

Applications

- Functional components for assemblies and mock-ups for:
  - Automotive styling parts — trim, fascia, and other components
  - Consumer electronic components
  - Toys
  - Snap fit assemblies
- Master patterns for RTV/silicone molding
- Replace CNC machining of polypropylene and ABS to produce short-run plastic parts
- Simulate injection molded parts
- Concept and marketing models

Features

- Look and feel of molded polypropylene
- High flexibility with excellent shape retention
- Outstanding feature resolution and accuracy
- High production speed
- Fully developed and tested build styles

Benefits

- Increased market opportunities for models
- Reliable and robust functional prototypes
- Suitable for master patterns
- More parts and better system utilization
- Maximize reliability with no user R&D

Automotive styling part.

Accura® 25 Plastic has high flexibility, while retaining the original shape.

STEREOLITHOGRAPHY

Accura® 25 Plastic

For use with solid-state stereolithography (SLA®) Systems

"Accura® 25 simulates the properties of a durable plastic in the range of polypropylene to low end ABS. The combination of its mechanical properties and its visual similarity to an injection molded plastic has led many of our customers to adopt Accura® 25 as their choice material for all models, unless otherwise specified. We have used it for customer applications ranging from durable enclosures and snap fit assemblies, to replacement parts for CNC machined delrin®. We have even had a few clients successfully use Accura® 25 parts as their production material for low volume applications. The properties and aesthetics make Accura® 25 the go-to resin for almost any application."

Todd Reese, President
Realize Inc.

Technical Data

Liquid Material

Measurement	Condition	Value
Appearance		White
Liquid Density	@ 25 °C (77 °F)	1.13 g/cm^3
Solid Density	@ 25 °C (77 °F)	1.19 g/cm^3
Viscosity	@ 30 °C (86 °F)	250 cps
Penetration Depth (Dp)*		4.2 mils
Critical Exposure(Ec)*		10.5 mJ/cm2
Tested Build Styles		EXACT™, FAST™, EXACT™ HR

Post-Cured Material

Measurement	Condition	Metric	U.S.
Tensile Strength	ASTM D 638	38 MPa	5,540 - 5,570 PSI
Tensile Modulus	ASTM D 638	1590-1660 MPa	230 - 240 KSI
Elongation at Break (%)	ASTM D 638	13 - 20 %	13 - 20 %
Flexural Strength	ASTM D 790	55 - 58 MPa	7,960 - 8,410 PSI
Flexural Modulus	ASTM D 790	1,380 - 1,660 MPa	200 - 240 KSI
Impact Strength (Notched Izod)	ASTM D 256	19 - 24 J/m	0.4 ft-lb/in
Heat Deflection Temperature	ASTM D 648 @ 66 PSI @ 264 PSI	 58 - 63 °C 51 - 55 °C	 136 - 145 °F 124 - 131 °F
Hardness, Shore D		80	80
Co-Effcient of Thermal Expansion	ASTM E 831-93 TMA (T<Tg, 0-20 °C) TMA (T<Tg, 75-140 °C)	 107 x 10^{-6} m/m-°C 151 x 10^{-6} m/m-°C	
Glass Transition (Tg)	DMA, E"	60 °C	140 °F

* Dp/Ec values are the same on all systems.

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Toll-free: 800.889.2964
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moreinfo@3dsystems.com
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NASDAQ: TDSC

Warranty/Disclaimer: The performance characteristics of these products may vary according to product application, operating conditions, material combined with, or with end use. 3D Systems makes no warranties of any type, express or implied, including, but not limited to, the warranties of merchantability or fitness for a particular use.

PN 70668 Issue Date - April 08

D.4 Aluminium Alloy EN AW 5083-H111 datasheet

PLACAS LAMINADAS

AW 5083

H111 LAMINADO

[AL Mg4,5Mn0,7]

Densidade **2,7 g/cm³**

WWW.KMS.PT

PRINCIPAIS CARACTERÍSTICAS

- Boa resistência mecânica
- Boa resistência à corrosão
- Boa maquinabilidade
- Boa soldabilidade
- Boa estabilidade dimensional

APLICAÇÕES

- Indústria naval e automóvel
- Peças estruturais e componentes para máquinas especiais
- Moldes para calçado
- Construção de equipamentos e dispositivos

PROPRIEDADES QUÍMICAS EN 573-3

	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
EN AW 5083	0,4	0,4	0,1	0,4 - 1,0	4,0 - 4,9	0,05 - 0,25	-	0,25	0,15

	Ga	V	Observações	Outros		Al min.
				Cada	Total	
EN AW 5083	-	-	-	0,05	0,15	Restante

PROPRIEDADES MECÂNICAS EN 485-2

Estado metalúrgico do material	Espessura especificada mm		Tensão de rotura à tração RM MPa		Tensão de cedência Rp0,2 MPa		Extensão após rotura min. %		Raio de dobragem		Dureza HBW
	Superior a	até	min.	max.	min.	max.	A50mm	A	180º	90º	
H111	0,2	0,5	275	350	125		11		1,0 t	0,5 t	75
	0,5	1,5	275	350	125		12		1,0 t	1,0 t	75
	1,5	3,0	275	350	125		13		1,5 t	1,0 t	75
	3,0	6,3	275	350	125		15			1,5 t	75
	6,3	12,5	270	345	115		16			2,5 t	75
	12,5	50,0	270	345	115			15			75
	50,0	80,0	270	345	115			14			73
	80,0	120,0	260		110			12			70
	120,0	200,0	255		105			12			69
	200,0	250,0	250		95			10			69
	250,0	300,0	245		90			9			69

STOCK AW 5083 LAMINADO

PLACA

ESPESSURAS

4 mm	5 mm	6 mm	8 mm	10 mm	12 mm
15 mm	20 mm	25 mm	30 mm	35 mm	40 mm
45 mm	50 mm	55 mm	60 mm	65 mm	70 mm
80 mm	90 mm	100 mm	110 mm	120 mm	130 mm
140 mm	150 mm				

DIMENSÕES DAS PLACAS	3000 x 1500 mm	2520 x 1270 mm	4000 x 2000 mm

Para outras dimensões, consulte-nos. Corte sob medida.

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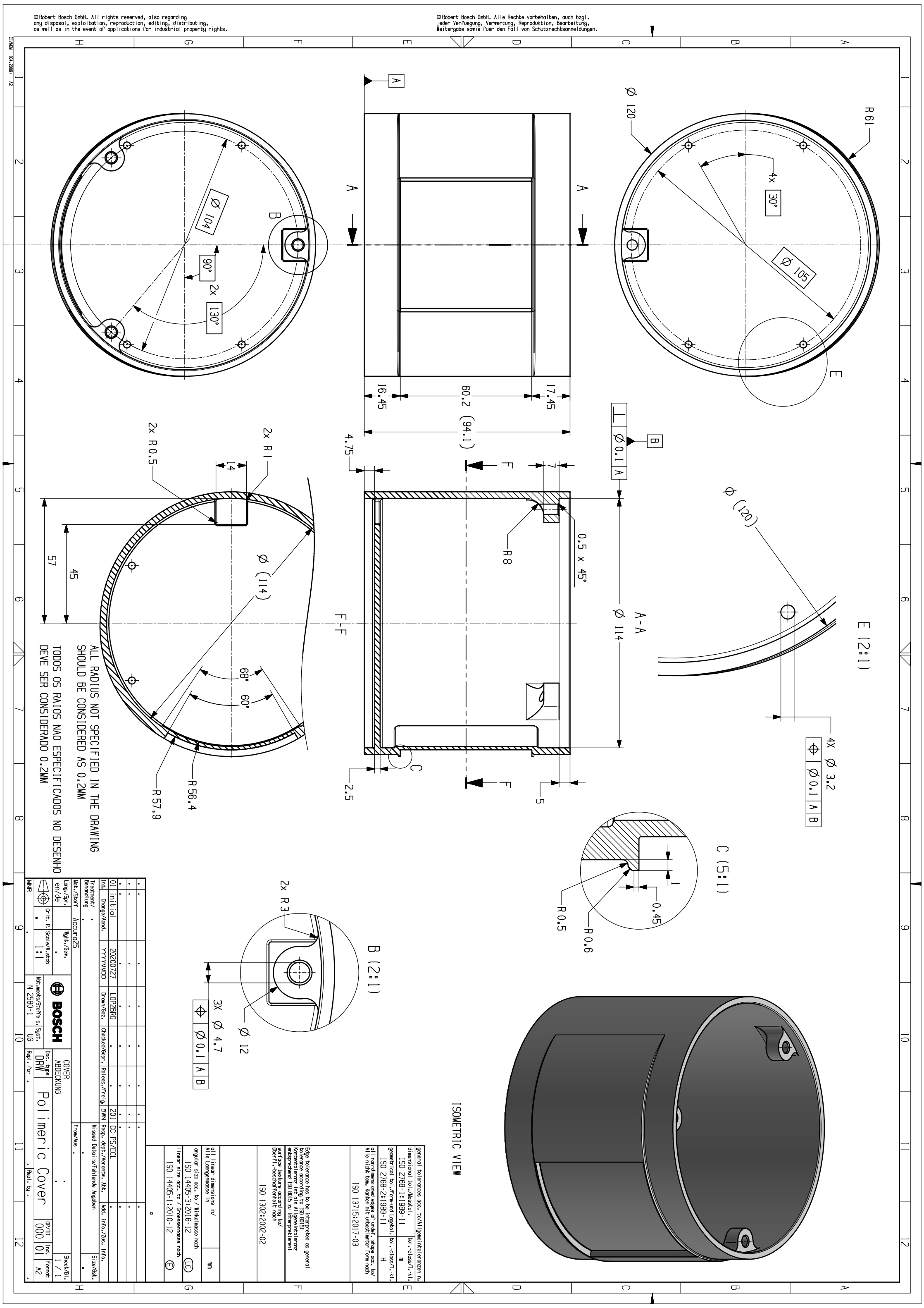
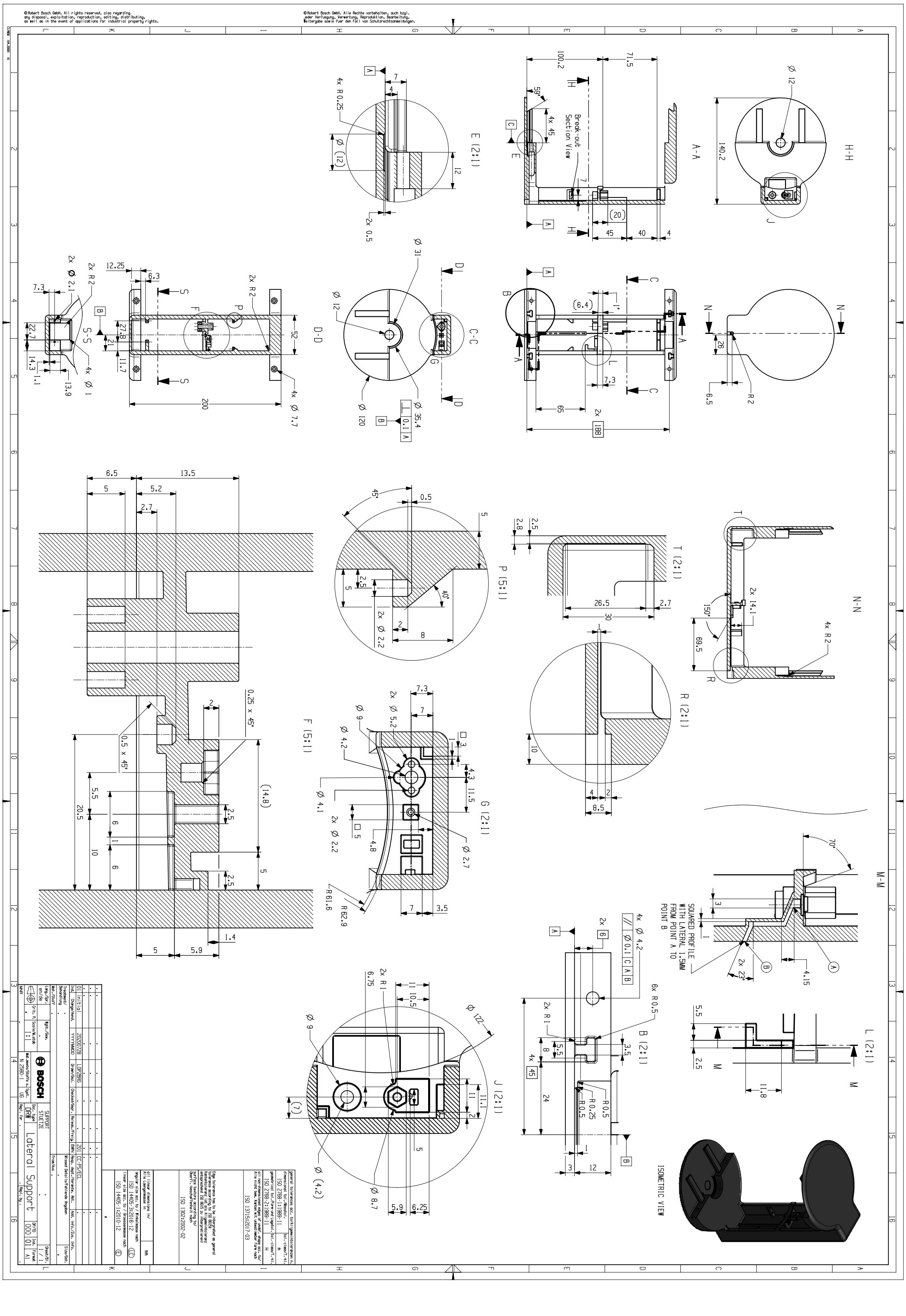
Appendix E

2D Drawings

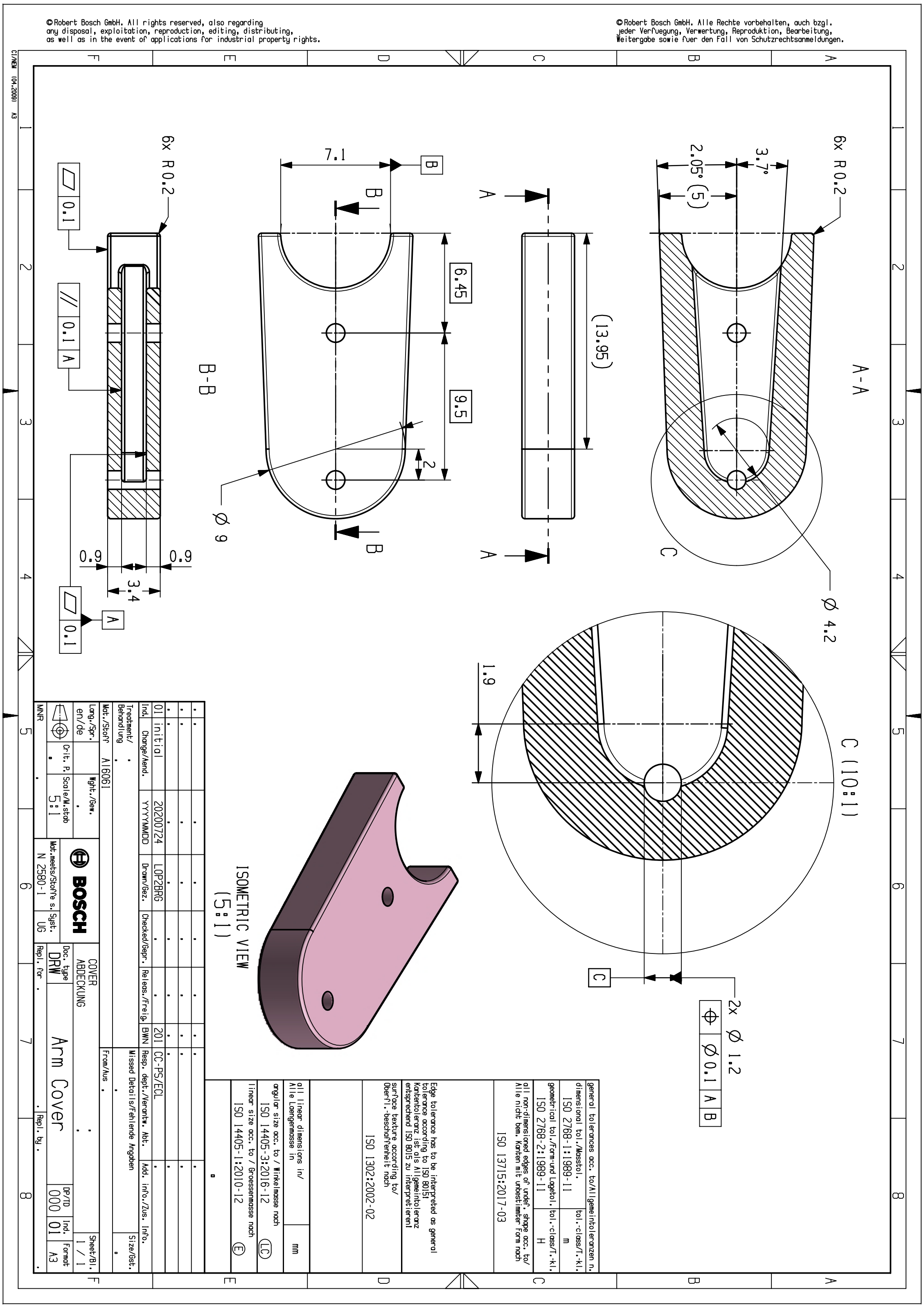
E.1 Polimeric Cover



E.2 Lateral Support



E.3 Arm Cover



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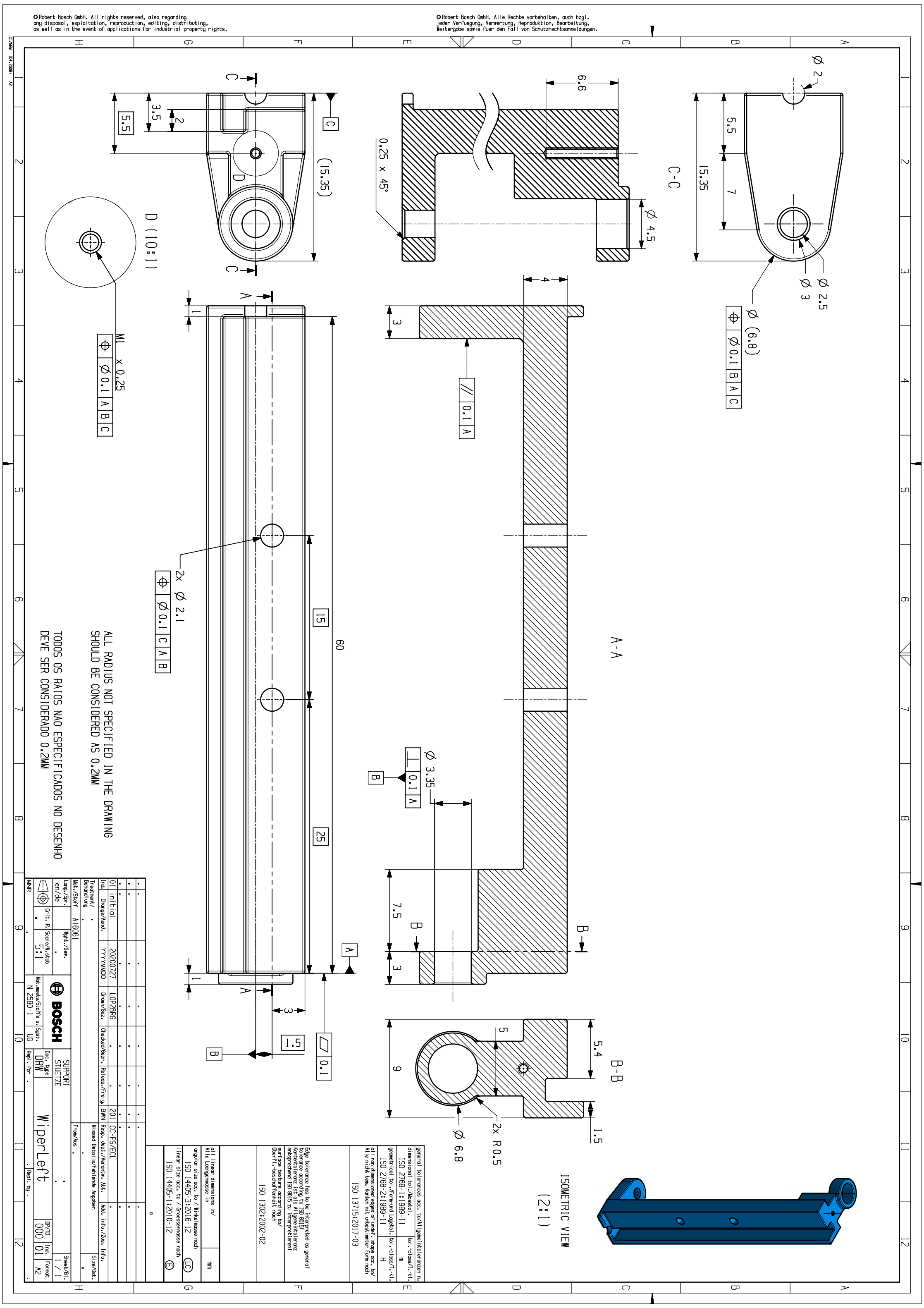
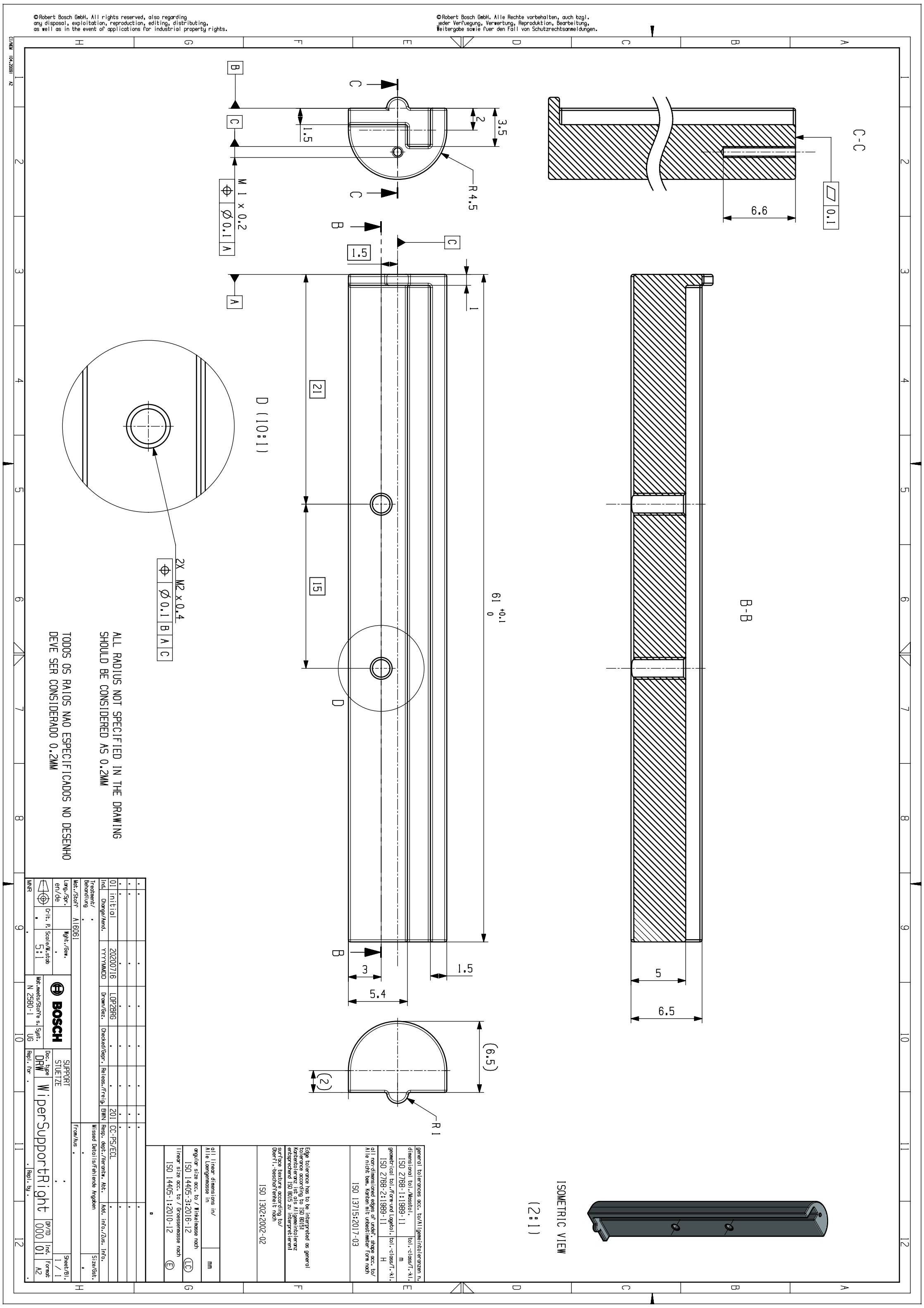
B-B
A-A
C (10:1)
ISOMETRIC VIEW (5:1)
6x R0.2
2x Ø 1.2
Ø 4.2
Ø 9
COVER
ABDECKUNG
Arm Cover
BOSCH
AL6061
5:1
DRW
A3
ISO 2768-1:1989-11
ISO 2768-2:1989-11
ISO 13715:2017-03
ISO 1302:2002-02
ISO 14405-3:2016-12
ISO 14405-1:2010-12

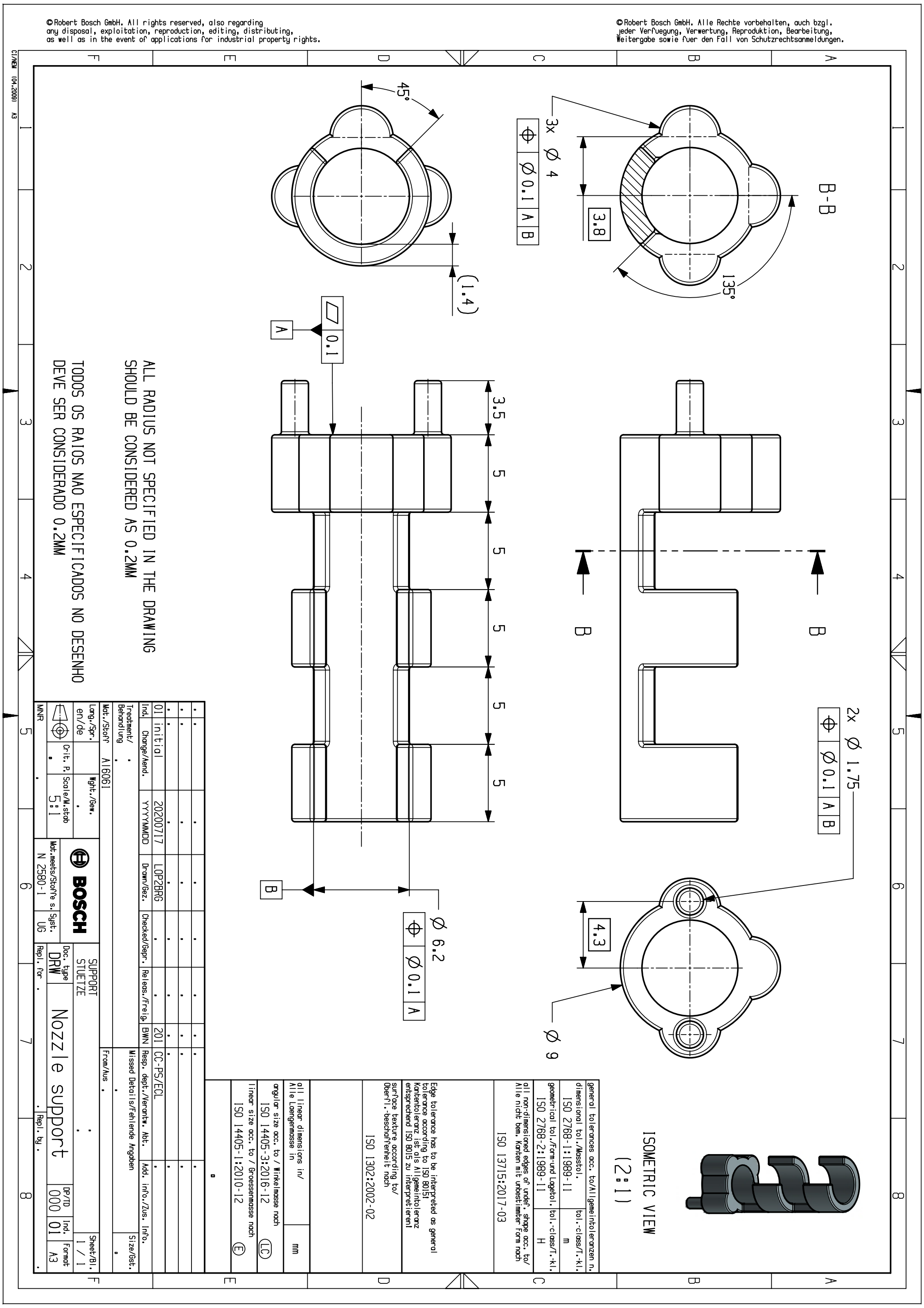
E.4 Left Support - Wiper



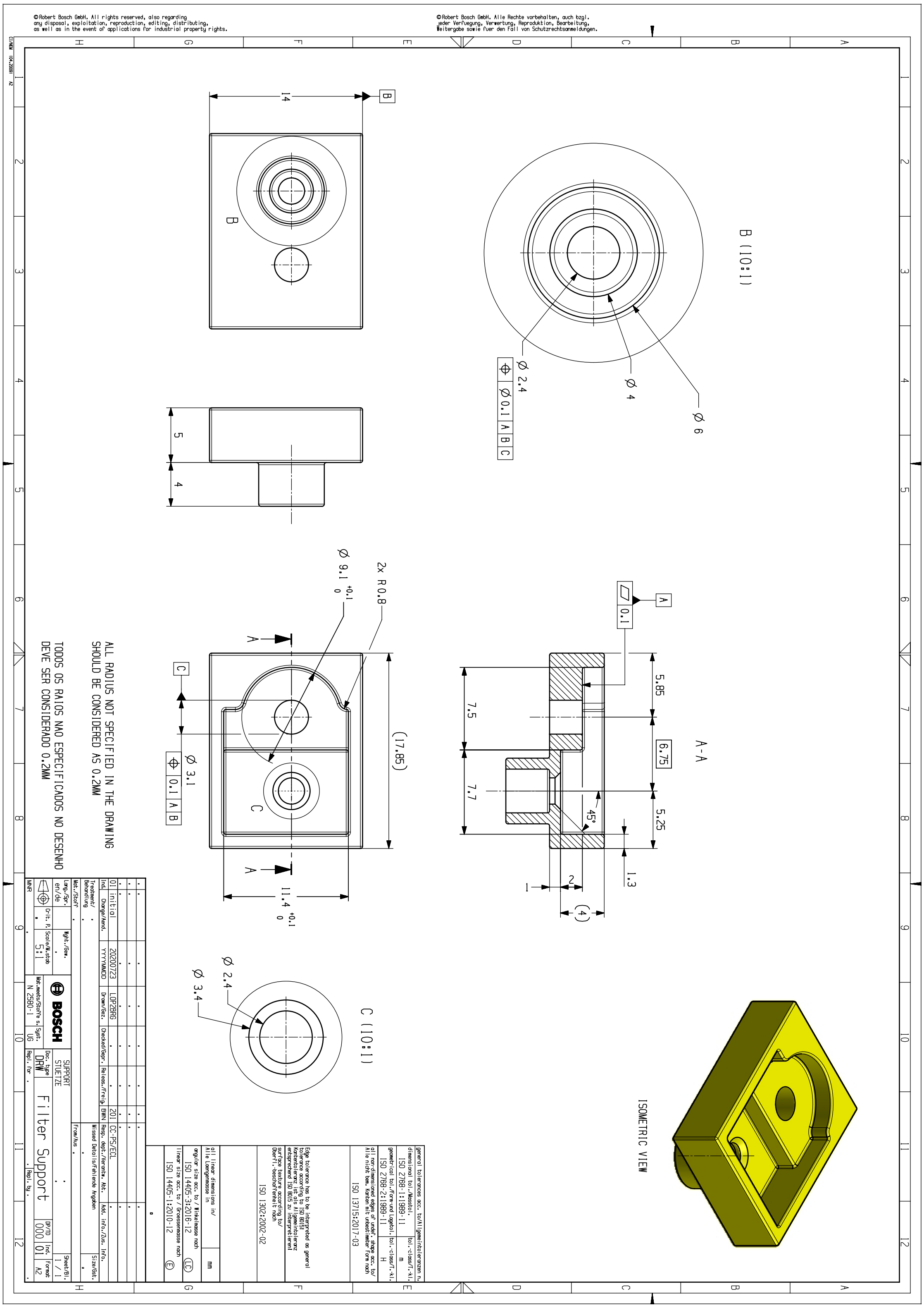
E.5 Right Support - Wiper



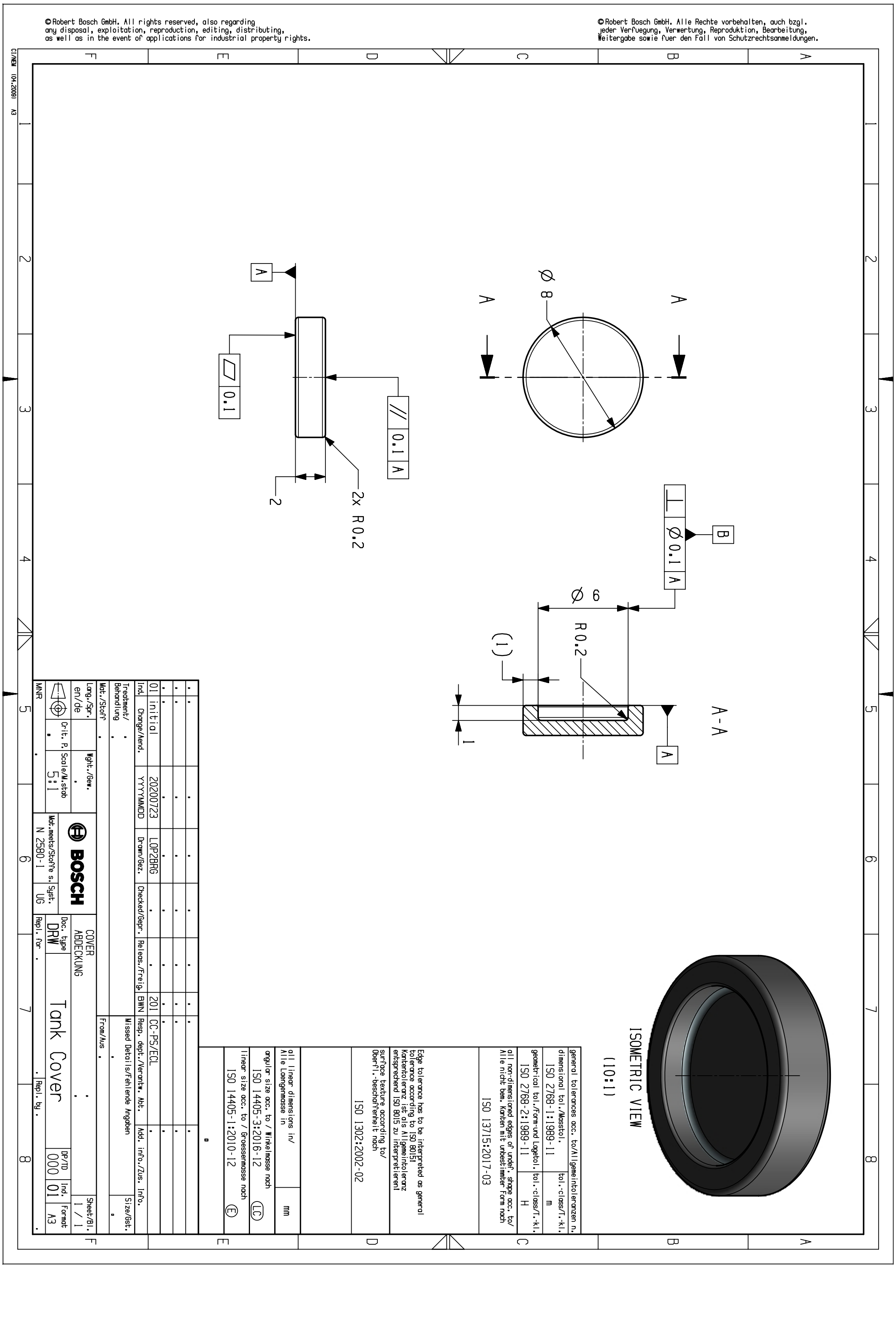
E.6 Nozzle Support



E.7 Filter Support



E.8 Tank Cover



E.9 Water Reservoir