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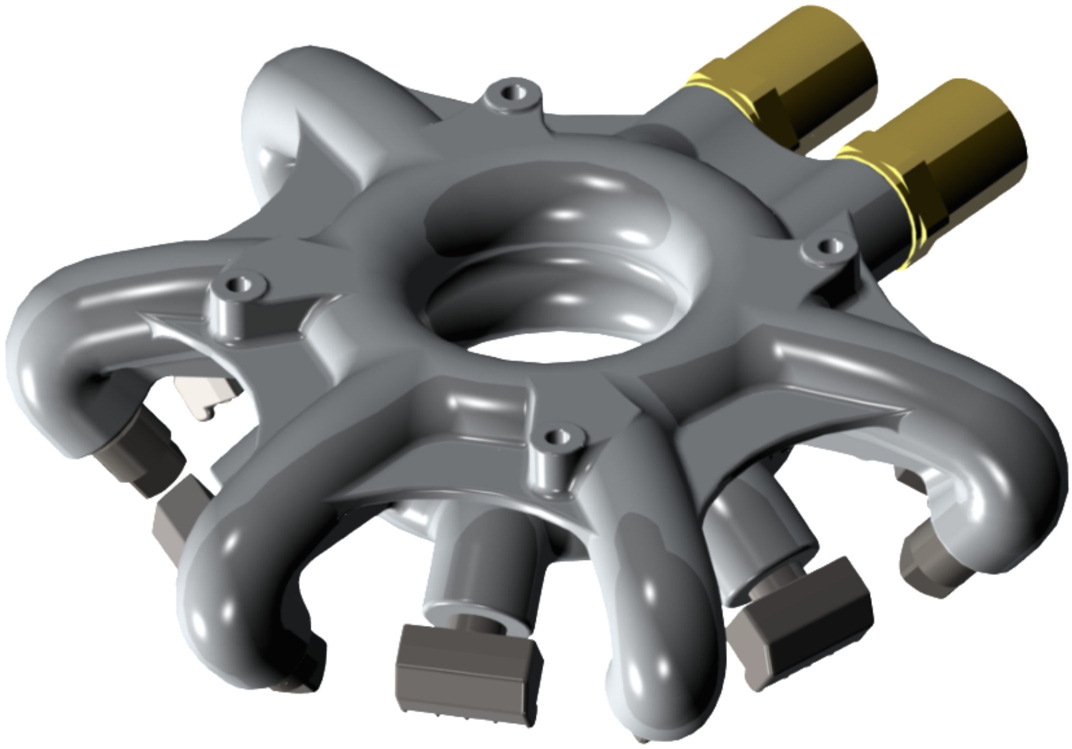

Development of a LiDAR Cleaning System for Autonomous Trucks

A Product Development Project at Volvo Trucks

Master's thesis in Product Development

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Department of Industrial and Materials Science
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Gothenburg, Sweden 2019

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Abstract

Autonomous driving is emerging as the future of transportation. For autonomous driving to be safe and reliable the perception sensors need sufficient vision in sometimes challenging operating conditions including dust, dirt and moisture. LiDAR perception sensors used in certain autonomous driving solutions require both a clean and dry sensor screen. The purpose of this thesis is that through developing and testing of concepts, provide Volvo with both knowledge and a baseline design to help with future product development of sensor cleaning systems in similar applications.

The developed concept for an improved cleaning system for the 2D-LiDAR sensors mounted to autonomous Volvo trucks are used in a mining operation. Emphasis in the concept is on the resource efficiency of the fluid available on the truck during operation. A cleaning head placed above the LiDAR does not compete for space with other systems around the LiDAR, allowing for greater design freedom. The prototypes indicate high potential in cleaning performance and as they were 3D printed in PA 12, proved a promising manufacturing method allowing complex geometries. The design combined with 3D printing also enables flexibility, allowing quick design changes to conform to different LiDAR shapes. Comparative testing against the currently implemented cleaning system is done in this thesis with dirt scenarios from intended to use-cases.

The result provides clear evidence of improvements against the current solution. Following an exploratory design and testing phase, it was concluded that great improvement in resource efficiency was achieved through the use of fluid specific nozzles, drastically reducing the fluid consumption of previous cleaning systems used by Volvo. Testing also gave evidence of existing knowledge gaps due to the novelty of the LiDAR cleaning task. This convinced the thesis workers that more research is needed and that standardized test methods need to be established to facilitate comparability between cleaning systems developed and tested in the future.

Keywords: Autonomous Driving, Autonomous Trucks, LiDAR, Sensor, Cleaning, Nozzle, 3D printing, Product Development

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Carl Gustafsson and Fredrik Karlsson, Gothenburg, June 2019

List of Abbreviations

AD	Autonomous Driving
ADAS	Advanced Driver-Assistance System
ADS	Automated Driving System
BSPP	British Standard Pipe Parallel
BSPT	British Standard Pipe Tapered
CAD	Computer Aided Design
FOV	Field of View
FMCW	Frequency-Modulated Continuous-Wave
GTA	Global Transport Application
IR	Infrared Radiation
LiDAR	Light Detecting and Ranging
MEMS	Micro-Electro-Mechanical-System
PA	Polyamide
PC	Polycarbonate
R&D	Research and Development
SLS	Selective Laser Sintering

Contents

1
Introduction

This chapter aims to provide the reader of this report with an understanding of the background to the problems creating a need for this project. The chapter also aims to provide the reader with basic knowledge and understanding of the company and the sub-division of the company where the thesis work is done. Sections with accounts of the aim and delimitations of the thesis work follows. The chapter concludes with an outline of the report.

1.1 Background

Volvo Group is a leading manufacturer of trucks, buses, construction equipment and engines and its headquarters is located in Gothenburg. The company was founded in 1927, is active in more than 190 countries and has more than 100 000 employees. Furthermore, Volvo Group is comprised of nine business areas. Four of which are related to trucks; Volvo Trucks, UD Trucks and JVs, Renault Trucks and Mack Trucks. The different brands allow the Volvo Group to better match different customer and market segments globally. The remaining business areas are; Volvo Construction Equipment, Volvo Buses, Volvo Penta, Volvo Financial Services and Arquus.

Special Vehicles Development in Gothenburg is a department within Volvo Trucks. The department's mission is to develop customized vehicles to customers where the number of vehicles is at least multiple and about 200 at the most. The projects generally last between a few months up to two years. It is together with Special Vehicles Development that the thesis work is conducted.

Volvo Group is making great efforts to develop the transport solutions of tomorrow, with significant resources invested in R&D. New solutions are needed to meet the changing and growing demands on transport from a wide range of industries. Volvo Group realizes the potential benefits of automated systems within the transport industry with benefits such as increased resource and flow efficiency. Autonomous vehicles have the potential to increase productivity and flexibility in a sustainable manner by simultaneously optimizing traffic management and energy efficiency. Therefore, it is of great importance for Volvo Group to continue the development of autonomous vehicles to offer competitive solutions and bring the benefits of automation to the market.

Automation in commercial vehicles is forecasted to increase in the future. Both Advanced Driver Assistance Systems (ADAS) and Autonomous Driving (AD) will have perception sensors as input for the automation system. A range of different sensor technologies is used, such as cameras, radar and LiDAR to collect needed data. Autonomous vehicles are classified based on their level of automation, from level 0 to level 5. Volvo Trucks will in 2019 deliver their first commercial autonomous vehicles to a limestone mine in Norway. The vehicles are fully automated. However, the transports are taking place within a limited area resulting in the trucks having automation level 4 [1], which means that the vehicles are capable to handle a defined use case without requiring human interaction .

Autonomous vehicles often use a multitude of sensors with different functions to perceive and react to the surrounding environment. Regardless of the sensor type, when installed on the vehicle it will be affected by the surrounding environment. To ensure the required level of performance from the vehicle, the sensors need its working conditions to meet certain requirements. A major contributor to the deterioration of the working conditions, followed by a decrease in the sensor's performance, is external factors such as dirt and/or rain- or snowfall. These external factors can either obscure sensors' intended field of view or inhibit signal inputs and/or outputs needed for the sensor to function satisfyingly. To, from a societal perspective, offer a safe autonomous solution the system needs to be redundant to the degree that the system allows for certain lowering in performance for periods of time. To reach desired levels of automation the system needs to have the capability to manage the disturbing external factors and re-establish working conditions that enable desired system performance.

1.2 Problem Description

The trucks used at the limestone mine use, among other perception devices, four 2D LiDAR sensors for positioning of the truck to its surroundings. The harsh conditions at the mine, predominantly a dusty and dirty environment, leads to the need for regular cleaning of the sensors.

Volvo Group sees the potential in an improved cleaning system, especially regarding performance and reliability, that could better withstand the conditions of the site to offer a competitive autonomous solution. Volvo has stated that improved performance regarding the release of the fluids used to clean the LiDAR will enhance the overall system competitiveness. Since the truck has constrained space for fluids, the amount of cleaning fluid that is brought is limited. Therefore, the regular cleaning of the LiDARs needs to be very efficient and optimized to achieve the needed performance. The timing of the release, the direction of release and the volume of fluids released is of significance to improve the solution. Excessive release of fluids leads to premature emptying of the tank holding the cleaning liquid, which is filled before every shift, leaving the system unable to perform further cleaning cycles during that shift. Improvement in cleaning performance and reliability would yield a system with better up-time and better cost-efficiency.

1.3 Purpose

The purpose of this thesis work is to develop a functioning and reliable sensor cleaning system compatible with the 2D LiDAR sensors and the truck model used at the limestone mine. Achievement of this purpose involves a design meeting the requirements set on the cleaning system due to the site-specific conditions present at the mine. The developed cleaning system must have the ability to clean the sensors entire Field of View (FOV). It should also fit within the geometrical and architectural limitations of the truck while fulfilling requirements set by Volvo and current legislation. The system must be able to provide cleaning for the four considered 2D LiDAR sensors without the need to take the truck out of service during a shift, under reasonable external conditions. Consequently, it is of interest to analyze the basic and specific parameters regarding what affects the trucks sensor vision, such as frequency and duration. This will enable reasonable optimization of the resources available during a shift for cleaning the sensors. Another criterion is that the suggested design should be of value for Volvo's future work. The design should exhibit sufficient flexibility allowing the entire system or specific components to be adjusted for other applications. It should also be designed to facilitate easier production due to potential future increases in production volume.

1.4 Delimitations

To encapsulate the core problem of the thesis and keep complexity and workload at manageable levels, the following limitations will be made.

The system will be designed for the road and environmental conditions present on the site of the project. This delimitation includes that meeting the specific legal requirements for transportation within the mining area will be of concern. However, the development process are to be carried out with the multitude of environmental scenarios in mind enabling the knowledge and the certain design aspects to be transferred to designs for other environments.

The thesis will regard a sensor cleaning system for the truck model currently used on the mining site. Since the project is ongoing at Volvo and design changes continues to occur, the design will be done for the truck layout presented to the thesis workers no later than 2019-02-28. The thesis workers have the authority to disregard changes by Volvo done at a later date, if they are not easily implemented in the design.

The design will mainly regard the hardware needed to achieve a functional cleaning system. The required system control and potential software will be checked for feasibility, but not developed within the thesis. Also an in-depth investigation chemical compositions of cleaning liquids will not be a part in this thesis.

The work focuses on developing the functionality of the system, leading to optimization of system performance. Cost and environmental impact will be considered as having lesser importance for the purpose of this project.

To simplify data collection and validation, artificial conditions similar to that of the mining site will be accepted for testing.

1.5 Report Outline

The report will follow the process of developing a prototype for a LiDAR cleaning system. Initially it will give a brief introduction to the core problem and the purpose of this project allowing the reader to gain understanding about the relevance of the project. This is accompanied with limitations set upon the thesis from the thesis workers and Volvo. The introduction is followed by a description of the methods used to complete the tasks in the project. The method chapter is followed by a theoretical chapter explaining the supporting systems, technologies and the requirements of the project. After the theoretical chapter follows a chapter of problem and requirement analysis. The report is then continued with a thorough walk-through of the concept development phase of the project, including results from the different development phases. The concept development chapter is followed by a chapter regarding the testing phase of the project, presenting both execution and results. Following the chapter on testing is a chapter presenting the final design proposal. This chapter gives a description of the final design, with potential design changes from the testing phase taken into account. The following chapter contains a discussion of the product in general. This regards the results throughout the project and factors affecting the results of the project. The last chapter contains a conclusion of the project, with final remarks of the project and its results, as well as guideline for Volvo's future development of sensor cleaning systems for applications similar to the one in focus of this project.

2
Methodology

The following chapter aims to provide the reader with insight into the intended work-flow as well as the theoretical and practical methods used within the thesis work. The chapter also provides the reader with information about the tools intended to be used during the thesis work, both in the form of software and hardware.

2.1 Workflow

The workflow of the thesis will use the *Generic Product Development Process* as a guideline and the steps taken within each phase will take inspiration from literature from Ulrich and Eppinger [2]. Within this thesis, the workflow is planned to end before *Production Ramp-up* since the production of the system is not considered in this thesis. The phases within this thesis are described in the sections below.

2.1.1 Planning

The planning phase will principally consist of two components, research and resource allocation. The research is done to provide the group with sufficient knowledge about the technologies involved in the core problem. Surrounding technologies will be researched if considered relevant. The knowledge gathering will come mainly from researching current solutions on the market, searching for limiting or beneficial IP from patents etc. and documenting information from knowledgeable resources in-house. The knowledge of in-house sources will be used for help in deciding the tools to be utilized during the design process.

Some steps in the planning phase in this project usually occur during the Concept Generation-phase, but are moved to the planning phase. This change is done because knowledge about the system usually gained from steps taken in the Concept Generation-phase is needed to plan the work efficiently.

2.1.2 Concept Development

In the Concept Development-phase, the knowledge gained during the planning phase will be used to create a functional decomposition to break down and make the problem manageable. After that, potential solutions are generated to the sub-problems on an aggregated level. These solutions will be combined into conceptual solutions and checked both against stated requirements and investigated for feasibility. During this phase, concepts will be given an industrial design and one or many feasible concepts meeting the requirements will go through testing for proof of concept. Data gathered from the testing will be used for the final selection of the concept, and the most promising concept will advance for further development.

2.1.3 System-Level Design

From the findings in the Concept Development-phase, system and product architectures will be developed. This includes defining necessary interfaces and the subsystems of the product. During the architectural design of the system-level design phase, close contact with affected members of the project group at Volvo is required. This is due to the implications the architectural design has on the cleaning system and other systems affected by the cleaning system. During this phase, refinement of the concept design and preliminary component engineering will be done.

2.1.4 Detail Design

The next step will be to finalize the design of the concept. The component engineering will be concluded by determining the final geometry and dimensions of the components. The components will be defined and modeled in CAD software. Simultaneously, the modeled components are to be assembled as assemblies and mounted to the truck model to geometrically assure compatibility and functionality. It is also during this phase that the material selection is planned to occur. Furthermore, standard parts from suppliers that will be used are evaluated and selected.

2.1.5 Testing and Evaluation

The detailed design will be transformed into a prototype during the exploratory Testing and Evaluation-phase. The phase will begin by designing a test plan to guide the process of testing the prototype. The test plan states the test methods that will be practiced. The focus will be on key requirements together with the overall performance. Finally, the results from the testing will be used as a basis for the evaluation of the design. The evaluation will be used to give recommendations for design changes for a final design proposal.

2.2 Methods

In this section, selected methods that will be used in the thesis are described in greater detail. In the description, both the approach and reasoning for achieving reliable results are presented.

2.2.1 Information Search and Analysis

When collecting the information, sources will be both primary and secondary to combine the two complementary ways of gathering the information. In the thesis work, mainly experts, suppliers and customers will be interviewed according to strategies described by Denscombe [3]. Interviews will be held one-to-one and in groups depending on what is possible to undertake and the level of discussion wanted to be achieved. The interviews will be held in a semi-structured fashion with questions prepared in advance. The approach ensures a focus on topics while allowing for flexibility and further probing. Mediating tools in the form of sketches, pictures, CAD-models and prototypes will be used to express questions and describe problems as well as support the evaluation of solutions and requirements. By preparing questions and bringing mediating tools, the interviews will be more productive and increase the knowledge gained. It will also ease the documentation during the interviews and make sure that the prepared topics are covered. Before each interview, the interviewees are contacted for an agreement about the time, place and duration of the interview to increase the convenience for both parties and ensure enough time is set aside. Documenting the answers along with asking confirming questions will aid in avoiding recalling false statements, reducing errors and bias handling of the information.

The process of secondary information search contains five steps starting with setting the scope of the search. After that, the search will be planned by preparing working documents as well as identifying information sources, search terms, questions and organizations of high relevance. When the plan is completed, the systematic search will take place to thoroughly search for information within the set scope. The information gathered will then be screened to reduce the data and determine the level of quality and relevance. Lastly, the remaining information will be categorized and summarized to do a final assessment. Emerging questions and gaps in knowledge that might still exist will lead to additional information searches and analysis. By redoing the process, knowledge from previous searches and progress in the project can be used to improve the process.

2.2.2 Patent Search

The patent search is based on the approach established by Haldorson [4]. To begin with, the scope with the aim of the patent search and its confines will be determined. This is followed by designing the patent search and accordingly identify classes, assignees and keywords to limit and optimize the search. The keywords are generated by answering a few questions stated about the invention. In the answers, describing words and corresponding synonyms are then selected as keywords. The keywords are used to create search strings using operators that will be used together with the relevant classes identified. The patent search based on these premises is to be carried out to find patents of relevance. The relevant patents will be analyzed and the process documented. The main patent database to acquire the information will be *Espacenet*, to account for patents in many countries.

2.2.3 Specification of Requirements

To visualize the functional criteria for the intended product a Specification of Requirements will be constructed. They will be categorized as requirements and desires, to provide information about the importance of each criteria. The requirements will be given a weight to further provide information about the importance of achieving the criteria. Each criteria is given a target value, visualizing the functional ability needed for the product to meet the criteria. Each criteria is given individual means to evaluate/verify the performance and a justification of the need for the individual criteria.

The specification of requirements will be utilized to coordinate the project and will be set early in the development of the product. Due to the build-up of knowledge and the potential change of requirements during the project the specification will be open for change during the project. The use of the specification in this thesis is due to its benefits in communicating targets in the present context [5].

2.2.4 Function-Means Modeling

To break down the functional requirements of the product designed in the thesis work and to facilitate the generation of sub-solutions, Function-Means Modelling will be done with the help of a Function-Means tree. This is done in a top-down approach through hierarchical levels by first stating the functional requirement on the highest level, followed by its possible solution or design parameter. There is a possibility that one functional requirement has several solutions. In a concept generation phase, it is beneficial to generate as many possible solutions to a functional requirement as possible. After the generation of solutions is done, the best sub-solutions for solving the functional requirement are combined. After a combination is chosen, the process is continued by generating sub-solutions on a lower level to the functional requirements that arise from the sub-solutions on the level previously handled [6].
Within the thesis work, certain limitations were set upon the solution, limiting the design space. This made certain parts of the tree to be out of scope and the approach of iterating the Function-Means Tree unnecessary. Instead, the tree was used as a solution generation and visualizing tool where the results were transferred into a Morphological Matrix. The transfer is done since the Morphological Matrix provides a better overview of the different solutions path of sub-functions and sub-solutions.

2.2.5 Morphological Matrix

A morphological matrix was used since it provides a structured way of combining solutions to sub-systems in the overall solution to the problem at hand. It also provides a scheme of tested combinations, lowering the risk of unnecessary work being done due to repetitive evaluation of similar concepts. In combination with a thorough evaluation, the morphological matrix can provide knowledge of a sub-solutions ability to stand alone or which other functions the specific sub-solution is dependent on. This information can prove vital in understanding the design space of the system.

2.2.6 Pugh Matrix

The Pugh Selection matrix, often called *Pugh Matrix*, was used in the concept screening phase of the thesis. The matrix is commonly used in an iterative manner evaluating generated concepts, in this thesis concepts from the Morphological matrix. The Pugh matrix evaluates concepts on criteria formulated from information gathered in the research of the problem. The concepts will be evaluated against a reference concept, based on if it is better, equal or worse than the reference. The matrix can also be designed with weights, giving certain criteria a bigger impact on the screening [2]. In the thesis, no numerical weighting was given to the criteria. Since one category of criteria was the most important for the solution, many criteria in that category existed in the matrix. This worked as a weighting of the matrix, giving concepts excelling in criteria of that category a better potential for a high score.

2.3 Tools

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

2.3.1 PTC Creo

At the location where the thesis work is performed, the CAD-software *Creo* is used when 3D modeling everything but the cab of the truck. Since the system of interest for this thesis is fitted to the chassis, *Creo* will be used when modeling for compatibility reasons. *Creo* also allows for lighter simulations of the model for proof of concept.

2.3.2 ANSYS

To provide a baseline for design decisions and to speed up the testing phase of the project, the software package *ANSYS* 19.2 will be used during the project. For static structural analysis *Workbench* 19.2 will be used. The structural analysis involves mainly stress and deflection analysis. For fluid analysis, *AIM* 19.2 will be used. The fluid analysis involves mainly getting initial information about high and low pressure points in regions with fluid-structural interaction as well as different fluid profiles.

2.3.3 KOLA

Konstruktionsdata Lastvagnar (KOLA) is a Product Data Management (PDM) System utilized by the Volvo Group. The system is foremost used in product development to document, manage and access information regarding variants and items of the trucks. The PDM system will help to collect and work with documents containing information of the truck on which the solution will be installed on.

2.3.4 Teamplace

Teamplace will be used as the online storage of all working documents in the thesis. The setup enables the sharing of documents between the two thesis workers and others involved in the project. Also, most documents related to the project is accessible in Teamplace.

3
Theory

This chapter aims to provide the reader with appropriate information about the technologies relevant to the thesis. The chapter starts with theory regarding different levels of driving automation. A description of LiDAR sensor systems follows. The theoretical description of the aspects of cleaning is also investigated. Relevant aspects of fluid mechanics, followed by theory regarding spray nozzles are also examined. This is followed by a section regarding relevant laws and regulations affecting the product. The chapter concludes with descriptions of the material and technology used for prototyping of the product.

3.1 Levels of Driving Automation

The American National Standards Institute manages a standard that recommends practices regarding driving automation referred to as *SAE J 3016-2018* The standard is also known as *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*. The document presents six levels of automation, commonly known as SAE levels in the industry. The levels are presented and described below [7]:

Level 0	-	No Driving Automation
Level 1	-	Driver Assistance
Level 2	-	Partial Driving Automation
Level 3	-	Conditional Driving Automation
Level 4	-	High Driving Automation
Level 5	-	Full Driving Automation

The levels of automation gradually increase with every level [7]. In the very first level, there is no driver assistance. For both level 1 and level 2, ADAS support the human driver who still has to monitor the driving environment. The automated systems of a vehicle with Level 3 only needs the human driver to be prepared and intervene when alerted. In level 4, the Automated Driving System (ADS) is capable of driving the vehicle in certain conditions without interventions from a human. Finally, level 5 corresponds to full driving automation that is not confined to certain conditions [1].

In the case of cars, the most advanced driving automation systems available reach automation level 2. This includes systems like the Tesla Autopilot and Volvo Pilot Assist II. To achieve this level of autonomy, multiple systems that use perception sensors are combined. Example of assisting systems are adaptive cruise control and lane assist [8].

3.2 LiDAR Sensor System

Light Detecting and Ranging (LiDAR) is a system that uses active remote sensing to perceive and map its surroundings. The light that is generated and emitted as pulses is in the form of light amplified by stimulated emission of radiation (laser). The emitted laser pulse reflects on a surface and the time it takes until the laser pulse returns to the LiDAR is registered [9]. There are a few different ways of measuring the distance to the objects on which the light is reflected. Time-of-flight refers to the most common technique where the time for the laser pulse to reach the object, reflect and return is measured [10]. The distance to the surface can after that be calculated with the knowledge that the laser pulse travels at the speed of light [9]. The formula to calculate the distance is the following [11]:

$$Distance = \frac{Speed\ of\ Light \times Time\text{-}of\text{-}Flight}{2} \tag{3.1}$$

There are four main approaches to directing the laser beam of the LiDAR [10].
A spinning LiDAR directs the laser beam by having the sensor system rotate around its axis. The fact that the LiDAR can rotate continuously results in coverage of 360° [10].

Mechanical scanning LiDAR redirects the laser beam by using a Micro-Electro-Mechanical-System (MEMS). The system revolves around a very small mirror that redirects the laser's beams in the wanted direction. The small size of the mirror enables rapid movements and consequently fast scanning of an area. The redirecting functionality allows for scanning patterns where certain areas are scanned with higher concentration. This, in turn, facilitates the identification of objects in the area that might be problematic to detect due to size or distance [12].

Optical phased array LiDAR directs the laser beam by adjusting the phasing between the arrayed lasers. This means that the lasers' phase relative to each other, changes the direction of the beam without any moving parts [10].

Flash LiDAR diffuses the laser beam to produce a wider scan, like a flash of the scene. The LiDAR is then equipped with multiple sensors to capture the returning laser beams [10].

3.3 Cleaning Parameters

The result from a cleaning process is mainly dependent on four parameters affecting the result of the process [13], see Figure 3.1. The parameters are *time*, *action*, *temperature* and *concentration*. Considering the case of equal occurrence of soiling and use of the same cleaning agent, these parameters can be altered while still yielding the same result as an increase in one parameter can compensate for the decrease of another. Other factors exists, which influence the required level of the parameters, such as *surface*, *soil levels* etc. [13]. A description of the parameters is found in the sections below. A description of the factors affecting cleaning can be found in Appendix A.

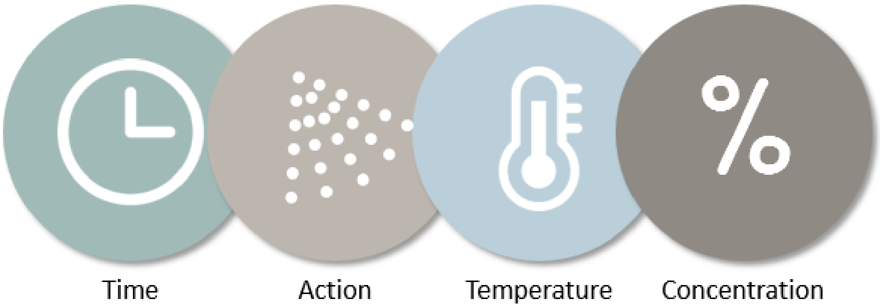


Figure 3.1: The four main cleaning parameters.

3.3.1 Time

A cleaning process yields better results if the soil experiences long exposure time to the action, temperature and cleaning agent.[13] But in some cases a long exposure time can be problematic. If the area being cleaned is exposed to cleaning for extended periods of time, the mechanical force, chemical agent or high temperature can impose damage on the area being cleaned. In many applications, such as the one present in this project, time is restricted due to the need for low downtime of the application being cleaned during the cleaning process.

3.3.2 Action

Action is the shear force acting on the soiled surface, such as a brush, a water jet or an air jet. Higher levels of force result in a higher probability of breaking the bond between the soil and the surface being cleaned. Higher forces also allow for the potential residue of soil, water or cleaning liquid to be removed from the surface [13]. One form of action is the impact generated by a nozzle that for instance spray water, see Section 3.5.3.

3.3.3 Temperature

Increased temperature has a positive effect on the cleaning process. An increase in temperature has effects such as higher solubility of the cleaning agent and faster reaction between the cleaning agent and the soil. High temperatures also decrease the viscosity of the soil, allowing for better penetration of the cleaning agent and removal from the applied force. Increased temperature can have negative effects on the cleaning process with an increased rate of corrosion of components and evaporative losses in the application of water and cleaning agent [13].

3.3.4 Concentration

Concentration refers to the concentration of a cleaning agent used during the cleaning process. Generally higher levels of concentration improve the result of the cleaning process as the cleaning agent aids in lowering the surface tension of the soiled surface. The environmental and safety constraints are the main limiter of the level of concentration [13].

3.4 Fluid Mechanics

The following section will describe certain relevant theory on fluid mechanics used during the thesis. The theory was used during the design of the product as well as for flow calculations and understanding of certain behaviour during testing.

3.4.1 Flow Rate

The volumetric flow rate is the volume that flows through a cross-sectional area over time. The flow rate can also be calculated using the velocity of the fluid. The velocity is the length of the fluid divided by the time, a term that is given when referring to the volume as the cross-sectional area multiplied by the distance [14].

$$Q = \frac{V}{t} = A \times v \tag{3.2}$$

Q	=	The volumetric flow rate
V	=	Volume of the fluid portion
t	=	The time it takes the fluid portion to flow through its length
A	=	Cross-sectional area
v	=	Velocity of the fluid at the section

The flow rate of a nozzle at a specific pressure can be obtained if the flow rate of the nozzle at another pressure is known, see Equation 3.3. As the difference between the pressures P_1 and P_2 increases, the deviation from the theoretical flow rate increases due to not accounting for several aspects. For instance, the equation only regards laminar flows, whereas turbulent flows most likely are present. Also, with increased velocity, friction losses increase. Furthermore, the amount of energy that is used to achieve a certain spray angle and pattern differs between nozzles [15].

$$Q_2 = Q_1 \times \sqrt{\frac{P_2}{P_1}} \tag{3.3}$$

Q_1	=	The nozzle flow rate at pressure P_1
Q_2	=	The nozzle flow rate at pressure P_2
P_1,P_2	=	Nozzle pressure energy

3.4.2 Losses

Losses occur in pipe systems, and parts of those losses are categorized as friction losses and minor losses. Friction losses are mainly a function of the system geometry, fluid properties and flow rate. Important factors increasing friction losses in a pipe system is long pipe lengths, small diameters of the pipe, high flow rates, high relative roughness of the pipe, the pipe cross-section and the Reynolds number [16].

Minor losses often contribute to a large portion of losses in a system. They occur at pipe entrances and pipe exits, gradual and sudden contractions or expansions of the pipe and different fittings and valves. The minor losses are summarized in a system and may account for a larger pressure loss than long pipes [17].

3.5 Spray Nozzle

Spray nozzles, also referred to as water nozzles, function as a way to increase the speed of a fluid and break it into droplets propelled by pressure energy. The process comprises of two steps, separating the fluid into droplets and directing the fluid. There are several applications of spray nozzles, among them is washing [15].

3.5.1 Spray Pattern

The choice of water nozzle design influences how the water is distributed by changing the characteristics of the spray. There are different designs of nozzles to achieve the desired performance for a specific application. Typical spray patterns produced by different nozzle designs are shown in Figure 3.2 [18].

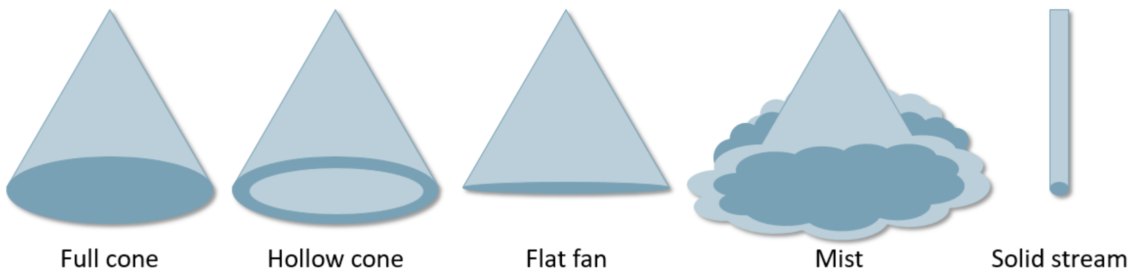


Figure 3.2: Spray patterns produced by different spray nozzles.

To obtain a *Full Cone* spray pattern, the water is distributed very evenly in droplets with spray angles between 30°-170°. The *Hollow Cone* spray pattern is in many regards similar to the *Full Cone* spray pattern, although the distribution is condensed around the cone's circumference. The *Flat Fan* spray pattern concentrates the distribution of water in a line with spray angles between 15°-145°. The spray pattern with the highest concentration of the water distributed is the *Solid Stream*. In contrast, the mist spray pattern is created shortly after the water departs from the nozzle and forms a uniform mist with little to no force [18].

Trigonometry is used to compute the theoretical spray pattern and thereby the surface area of the spray pattern. The calculated theoretical spray pattern is less accurate further away from the nozzle as the spray is affected by several factors.

The actual spray pattern caused by the following factors; gravity, viscosity, flow rate, pressure and nozzle design has a smaller spray coverage [18].

3.5.2 Droplet Size

There is a relationship between droplet size and the surface area of the spray. By doubling the surface area, the mean droplet size is reduced to half. Hence, a wider spray angle results in smaller droplets, partly because there is less chance of the droplets recombining. A *Hollow Cone* nozzle produces the smallest droplets while a *Solid Stream* nozzle does not separate into droplets. In cases of moving flows in the proximity to the spray, such as wind, smaller droplets are more affected and might be redirected and miss the targeted area, called spray drift [18]. In general, higher pressure creates smaller droplets by atomizing the spray. The same is true for lower flow rates if the pressure remains the same [19].

3.5.3 Impact

The impact of a spray, the measure of impact force divided by the surface area [19], is important when it comes to cleaning. An increased pressure affects the impact by increasing the internal energy of the fluid. The type of nozzle alter the proportions of energy that is used to atomize the spray and increase the impact of the spray. Consequently, a nozzle that produces a *Solid Stream* is very efficient in transferring the internal energy to impact force as it does not atomize the fluid [18]. The impact increases at the same rate as the pressure when ensuring that the flow rate remains the same. It is also possible to increase the impact, as long as the pressure is kept, by increasing the flow rate [19].

Flat Fan and *Solid Stream* spray pattern is often utilized in washing operations to ensure a high impact to remove residue from a surface. These spray patterns are however limited to the area that the spray is distributed and require motion to clean an area [20]. As the relation of impact force and surface area state, the impact is reduced with an increase in surface area. By increasing the distance between the nozzle and the surface, the surface area sprayed by the nozzle enlarges leading to reduced impact[19].

3.6 Laws and Regulations

The general maximum allowed total width of a motor vehicle is 2550 mm, including the type $N3$ used at the mining site [21]. Apart from rear-view mirrors, devices and equipment are generally not allowed to have a total protrusion adding to the width larger than 100 mm. LiDARs are to be considered as watching and detection aids, and are therefore not included in the regulation [22]. The maximum allowed protrusion of mounted equipment in front of the truck in the forward direction of the truck is 250 mm. Units and equipment mounted on the truck, both in the front and in the rear of the vehicles, must not protrude more than 750 mm combined.

3.7 Polyamide and Selective Laser Sintering

The solid polymer Polyamide (PA) 12, often known as Nylon 12, is referred to as PA 2200 when in powder form. PA 12 is regularly used for rapid functional prototypes and small productions of 300-1000 parts [23]. Table 3.1 presents important material properties regarding PA 12 [24].

Table 3.1: Material properties of PA 12.

Measurement	**Value**	**Unit**	**Standard**
Density	$0,95 \pm 0,03$	g/cm^3	
Tensile Strength	48 ± 3	MPa	DIN EN ISO527
Tensile Modulus	1650	MPa	DIN EN ISO527
Heat Deflection Temperature	86	$°C$	ASTM D648 @ 1.82MPa
Chemical Resistance	Yes [25]		

Selective laser sintering (SLS) is an additive 3D printing technology. The process starts with a thin layer of powder that is applied to the printing surface. The laser selectively heats the desired cross-section of the part to less than the melting point of the material. The heat fuses the particles of the powder. The process is repeated for each layer, forming the complete part layer by layer. SLS can create complex geometries without the use of support structures as the un-sintered powder acts as support during the printing [23]. The residual powder is thereafter removed, unveiling the part with a surface texture that is optional to finish [24; 25]. The accuracy of the SLS manufacturing process is $\pm 0,3$ % with the lower limit of $\pm 0,3$ mm [25].

When manufacturing a part in PA 12 with SLS, several guidelines direct and affect the design. The un-sintered powder in internal channels might be difficult to remove. It is therefore recommended to have a diameter larger than 3 mm for internal channels in the part. For larger wall thicknesses, thicker than 9 mm, it is suggested to hollow out the solid part to counter tendencies of deformation. Warping is another kind of deformation that occurs if the part has a flat plane that is too large. Furthermore, wall thickness greater than 1 mm is recommended [26].

4
Problem and Requirements Analysis

This chapter aims to provide the reader with information about the problems and requirements. The chapter begins with a section containing a market analysis of the market on which the product acts on. The chapter is continued with relevant project and system information enabling a better understanding of future design decisions. Lastly, the specification of requirements is compiled.

4.1 Market Analysis

The market for self-driving vehicles is increasing and the number of companies competing for market shares in automotive-grade LiDARs is increasing. LiDAR has in later years been a crucial component in self-driving vehicles and experts see LiDARs as being a crucial component in self-driving vehicles in the foreseeable future [12].

As a part of preparing for and aiding the concept generation, a patent search was performed during the planning phase of the project. The reason for the search was to find where the risk of infringements on intellectual property was present and how this affected the design space of the thesis work with respect to its aims. In the patent search, no limiting patents were found that affects the design of the cleaning head. From the market search and patent search is was also evident that few cleaning systems for sensors exist in automotive applications in general, and for LiDARs in particular. Conceptual designs exist for sensor cleaning systems, predominantly for cars. However, a majority of the cleaning systems on the currently under development are made for significantly different conditions than the conditions present at the project site.

Since no other comparable system could be found on the market the projects current cleaning system will be used for benchmarking during the thesis.

4.2 Project Information

During the information search of the thesis, knowledgeable employees at Volvo were contacted and interviewed in different setups, see Section 2.2.1. This was done to get a nuanced view of the problems and requirements. Studies of literature, mostly online, were performed to gain information that was not attainable in interviews. Often the two approaches were used as a complement to each other. Certain company guidelines for Volvo's development process regarding different applications were also investigated to better understand requirements set on the product by factors such as operating environment and transport mission, see Appendix B.

4.2.1 The Mine

The mine is an open-pit limestone mine situated in the central part of Norway. The mine extracts limestone that is transported from the extraction point in the open-pit mine through a series of tunnels, see Figure 4.1, to an unloading site on the edge of a fjord. The trucks unload the limestone into a processor that crushes the limestone which is then transported by conveyor belts and loaded onto ships waiting in the fjord, see Figure 4.2.

Figure 4.1: Autonomous Volvo truck driving in one of the tunnels.[27]

4.2.2 Volvo's mission

Volvo's role in the project differs from Volvo's normal products. Volvo's normal operations have its foundation in selling trucks to customers and offering after-sale services. In this project Volvo sells a result-oriented service based on a functional result [29], in this case transporting raw material from A to B, instead of selling the

Figure 4.2: Autonomous Volvo truck offloading at the crusher.[28]

product. This provides new challenges for Volvo since aspects of the operation that previously required little or no consideration now gets a high priority. One aspect of this is cutting the costs occurring during the on-site operation. Volvo aspires to do this through automation of transportation, removing cost associated with the drivers and enabling high efficiency through optimized routes and driving behaviour. This operational strategy provides new challenges for Volvo by increasing the requirement on up-time and utilization of the trucks on the site and through that minimizing the cost per unit distance.

4.2.3 Site Conditions

The mine is an open-pit limestone mine. The method of extraction, loading, unloading and transporting of the limestone leads to fine dust being spread into the surrounding environment. The roads at the sites are maintained dirt roads, which especially under dry conditions, leads to increased spreading of dust to the surrounding environment.

The mines geographical position leads to the mining site being classed as having a warm and temperate climate [30]. The average annual temperature is approximately 5.5 °C and varies with around 15 °C throughout the year. The site has four months with an average temperature below 3 °C, meaning that the site experiences perception both as rain and snow. The annual average precipitation is around 1400 mm.

The external conditions present at the site in combination with the type of roads at the mine leads to the trucks, and also the LiDARs, being exposed to a substantial amount of mud splashes and swirling dust.

4.3 Description of the LiDAR System

In the following section, the current cleaning system and supply systems associated with it will be described. A description of LiDAR currently used is also given in the section.

4.3.1 LiDAR Helmet

The LiDARs are installed in multi-functional helmets, see Figure 4.3, that are mounted to the truck with bracers. The bracers are fixed to the truck's chassis to not be exposed to the additional dampening of the cab. To enable the multiple LiDARs' horizontal scan plane to be aligned, the positioning in the helmet is adjustable. Furthermore, the interface between the helmet and LiDAR is suspended to counteract minor vibrations. Another important function of the helmet is to protect the LiDAR from precipitation and contamination present during operation. The helmet is therefore designed with protective covers with a narrow horizontal gap to allow the LiDAR to operate. These multiple functions require certain geometrical space that impacts where and how the cleaning system is possible to be integrated. However, the LiDAR helmet is subject to a major re-design concurrently with the thesis work. For that reason, the development of the new cleaning system considers the new helmet when designing. Simultaneously, the new design should also consider production aspects to efficiently accommodate a potential future increase in production volume.

During operation, the trucks are exposed to vibration due to a combination of speed and the road conditions present at the mine. The vibrations are particularly harmful to parts and systems with a long lever from its center of mass to its fastening point, such as the LiDAR helmet. The long lever increases the moment generated by the acceleration of mass-produced during vibration and by that the stress in affected parts. For this reason, it is beneficial to minimize the weight of the helmet, cleaning system and LiDAR. This becomes evident when investigating an S-N curve, where it can be seen that a reduction in stress amplitude leads to an increasing number of load cycles a component can withstand [31].

Figure 4.3: Current LiDAR helmet installed in the project. The picture is cropped.[32]

4.3.2 LiDAR

There are several 2D LiDARs mounted on the autonomous trucks at the mining site of the model *SICK LMS111-10100*, see Figure 4.4. SICK's 2D LiDARs redirect the laser with a mirror that rotates [33]. One LiDAR is placed on each corner of the truck's cab. The horizontal angle of the scanning range is 270° [34], see Figure 4.5. The 90° that is out of the scanning range faces the cab.

Figure 4.4: 3D rendering of a SICK LMS111-10100 2D LiDAR.

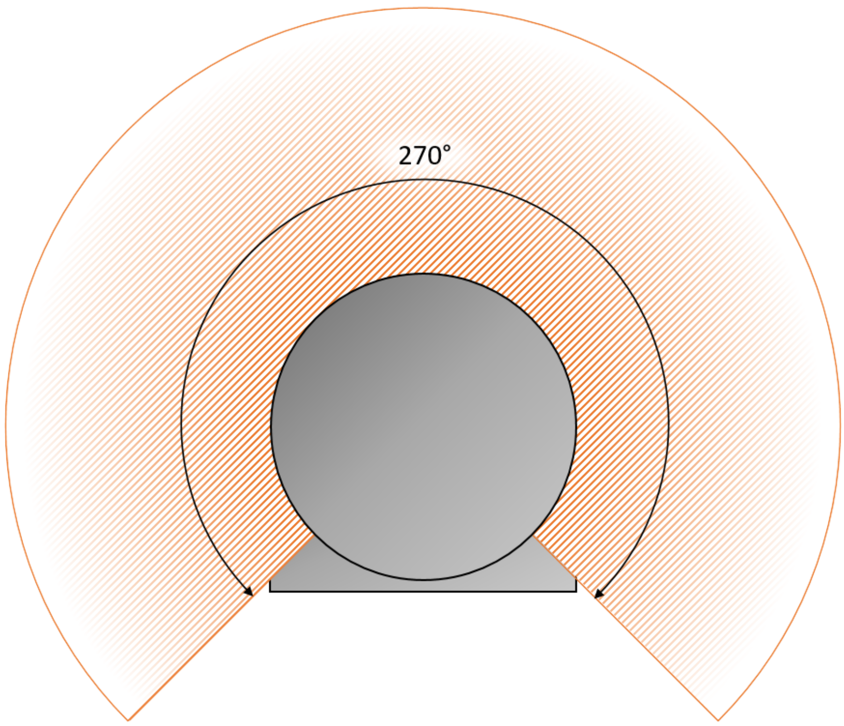


Figure 4.5: The horizontal scanning range angle of the LiDAR.

The positioning of the LiDARs results in the LiDARs' FOV overlapping, see Figure 4.6. This allows up to two LiDARs to be blind at any one time while the truck continues to operate. However, there are situations such as both front LiDARs being blind that limits the FOV too much and thereby require cleaning for the vehicle to be operational.

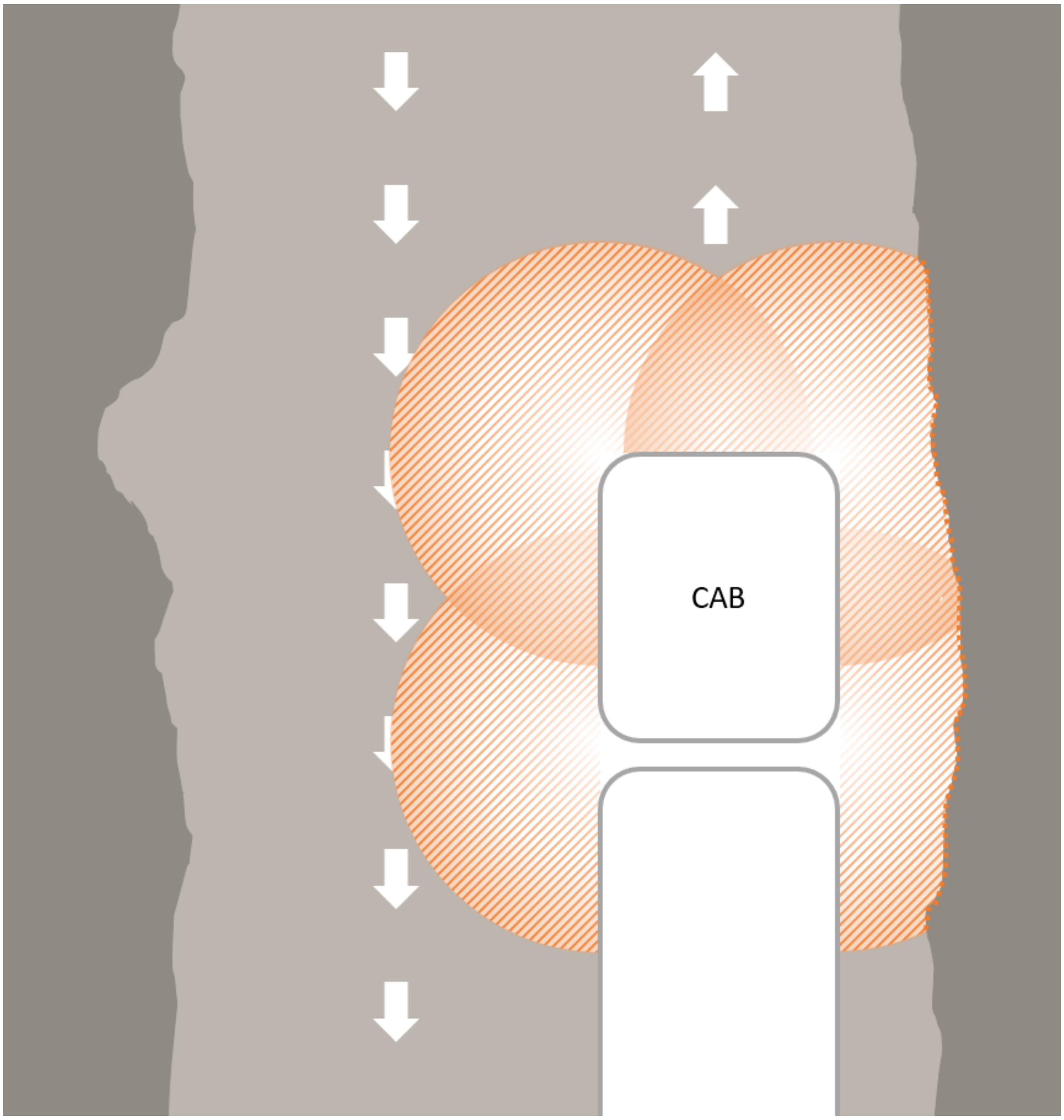


Figure 4.6: The positioning of the four LiDARs and their FOV overlapping

The LiDAR of interest emitts a short pulse of laser light that diverge with an angle of around $0,43°$, see Figure 4.7. The size of the beam diameter is calculated with the following formula [34]:

$$Beam\ diameter = (distance\ [mm] \times 0,015rad) + 8mm \tag{4.1}$$

Moreover, Figure 4.7 also illustrates that the reflected beam requires a vertical gap of a minimum of 15 mm with a horizontal gap of a maximum of 200 mm from the center axis. This is required for the protective helmet not to interfere and block the receiving pulse. Not following these guidelines might drastically reduce the ability of the LiDAR to acquire accurate results. The same is true for surfaces that reflect sun glare at the LiDAR optics cover causing blind spots [34].

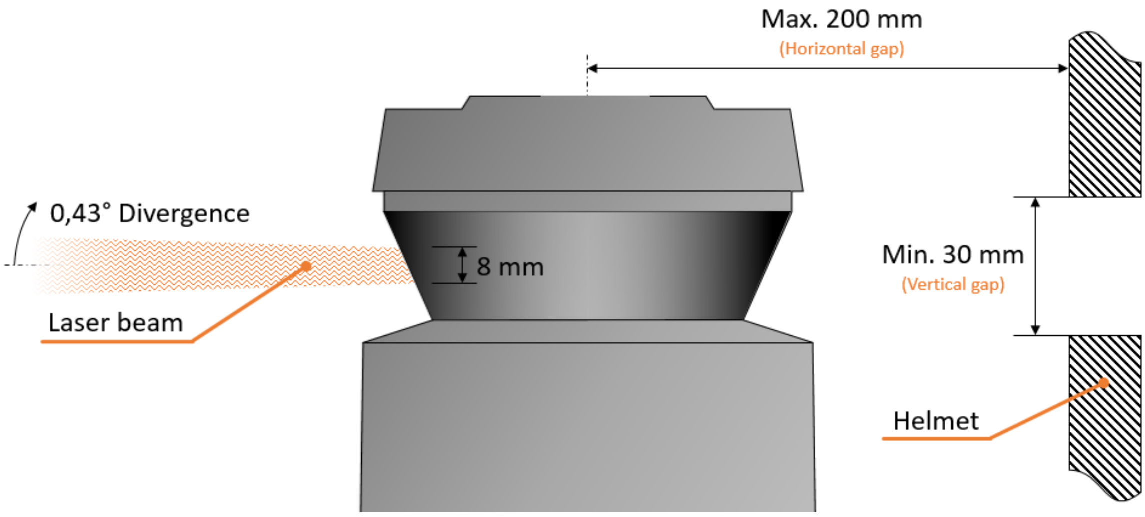


Figure 4.7: The divergence of the laser beam is visualized to the left. The minimum vertical gap at the maximum horizontal gap for the receiving laser beam is visualized to the right.

The LiDAR has a built-in solution to determine if and how obstructed the optics cover is. Below the LiDAR's optics cover there is a shelf in which seven IR-sensors are located, positioned $38,6°$ apart from each other in a radial pattern, see Figure 4.8. These seven IR-sensors send beams through the optics cover to thereafter be reflected to receivers that determine the level of cleanliness of the optics cover [34].

The optics cover is made out of Polycarbonate (PC) with a surface area of $6,48249 \times 10^{-3} m^2$. The optics cover is protected with a PHC 587 silicon coating and additional additives to achieve both protective and hydrophobic properties [34]. According to the technical data sheet of a comparable coating, it is resistant to chemicals and solvents such as oils, fuels and washer fluids. The protective layer is also abrasion-resistant and mar-resistant to withstand for instance sand and dirt [35]. However, the operating instructions of the LiDAR state that the maintenance in the form of cleaning the optics cover should be cleaned in a certain manner. No aggressive detergents or abrasive cleaning agents should be applied when cleaning. Also, the manufacturer recommends a soft brush and damp lens cloth to remove dust and wipe the optics cover clean [34].

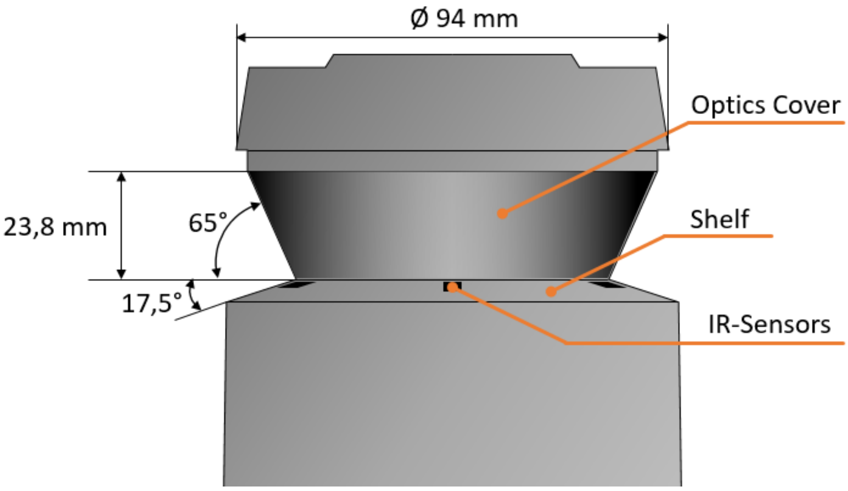


Figure 4.8: Description of the 2D LiDAR SICK LMS111-10100 with important features and dimensions indicated.

4.3.3 Current Cleaning System

The project is the first project of its kind that Volvo has undertaken at this scale. It is case-specific, leading to very specific requirements on the truck and its systems. The specific nature and novelty of the project creates a lack of set requirements since there are limited prior knowledge about the application and no comparable products to benchmark against.

The truck has a limited amount of cleaning liquid leading to Volvo wanting an improvement of the fluid distribution in the new solution in comparison with the current solution. The truck carries one 25 liter tank carrying the cleaning liquid while the compressed air is generated and stored in a separate tank. To control the distribution of each fluid, solenoid valves are installed along with each hose close to the cleaning system of each LiDAR. The hoses of the two fluids are merged directly after the solenoid valves. Consequently, one hose is connected to the single inlet of the current cleaning system.

The current cleaning system directs both the cleaning fluid and the air from below the optics cover of the LiDAR. The fluids are distributed through the same nine holes situated around the LiDAR, except at the back which faces the cab. The hole design creates a spray pattern similar to the *Solid Stream*, see Section 3.5.1.

4.3.4 Air Supply

The air in the cleaning system is supplied from the central air system installed on the truck. This system serves several vital systems on the truck, including the brakes and often parts of the suspension. The air pressure is created by a compressor situated close to the engine in the engine bay of the truck. The maximum pressure of the air system is $12,5$ bar. Several vital systems on the truck use air from the same supply leading to different systems being given different priority.

To be able to uphold vital functions of the truck, such as breaking, the cleaning system is of lower priority. For this reason the cleaning system can only be used when the pressure in the system is above the cut-off level, set at 8, 5 bar. This is a safety feature as a truck must always have the ability to stop. The LiDAR system is designed to allow collaboration between the LiDARs so that not all LiDARs must be clean at all times, see Section 4.3.2. The air is distributed through a regulating block on the frame and distributed to the cleaning system through hoses running along the frame of the truck.

4.3.5 Cleaning Liquid

For the washing of the LiDARs, an application-specific tank containing cleaning liquid is installed on the trucks at the mine. The tank can hold 25 liter of liquid and is installed on the frame of the truck. The liquid that is used is a mixture of water and regular washer fluid. The tank is pressurized by compressed air supplied by the main air system, which propels the liquid through hoses to the LiDAR in need of cleaning. The liquid is directed to the correct LiDAR through a distribution block mounted on the frame of the truck.

4.4 Specification of Requirements

4.4.1 Preface to Specification of Requirements

Due to the novelty of the cleaning system and its application, Volvo and other stakeholders were shown to have no prior requirements set upon the product developed in the project. However, different tests of the truck at the mining site lead to Volvo having perceptions of potential needs and requirements. The group therefore worked to compile acquired data and information about the involved technologies to translate these into a *Specification of Requirements*. Included is a limited number of statements gathered from personnel in the project that have been translated into requirements and desires. The novelty of the product causes the acquired specification to be better used as recommendations for the group to work towards in the development process. Since the requirements were specified throughout the entire duration of the project, the specification was developed over time. New information was constantly acquired and new inputs led to changing perceptions, even to the most important requirements.

4.4.2 Utilization of Specification of Requirements

The *Specification of Requirements*, in its various levels of completeness, was used throughout different stages of the project. It was used for setting the baseline when generating and evaluating concepts. During the design phase, it was used as a checklist to ensure that important design parameters were met and the desired functionality could be expected from the design. The *Specification of Requirements* was also utilized when designing the tests and analyzing the results. The approach ensured that the tests were designed to acquire answers to the most important knowledge gaps in the design's functionality. The analysis of the tests was also checked against the *Specification of Requirements* to map where the design met requirements and where more testing or possible design changes were needed.

4.4.3 Requirement Specification

The *Specification of Requirements*, see Table C.1 in Appendix C, is divided into six main areas. This was done to aid a better overview of fulfillment based on functional categories. The *Specification of Requirements* contains seven columns. First, the criteria order number is stated. Secondly, the criteria is stated followed by a target value in the third column. The fourth column states whether the criteria is a requirement or a desire and the fifth column states if the criteria is a desire, the weight of importance of the desire. The weights are based on a scale of 1 - 5, where 5 denotes the highest rate of importance. The sixth column states the method of evaluation or verification of the criteria. The seventh column states the justification of criteria.

From the complete specification of requirements, twelve criteria are regarded as being more important to develop a successful cleaning system, see Table 4.1. At an early stage, the importance of limiting the consumption of liquid was understood. The criteria 1.5 showcase this with the target value of less than $0,25$ liter per cleaning sequence. The amount corresponds to 100 cleaning sequences with a liquid tank of 25 liter. Criteria 1.6 states that the air is limited at times, even though it is generated on the truck. Criteria 1.7 - 1.9 are importance since they are requirements for the LiDAR to function as intended, see Section 4.3.2. The flexibility regarding the time is set with criteria 1.12 and 1.13. Criteria 1.15, 1.18 and 1.19 all focus on the result to be achieved by the cleaning system. Finally, the optics cover of the LiDAR should not be damaged over time, which criteria 2.4 defines.

Table 4.1: The twelve most important requirements and desires.

	Criteria	Target value	R/D	Weight
1.4	Liquid usage per successful cleaning sequence	< 0,75 L	R	
1.5	Liquid usage per successful cleaning sequence	< 0,25 L	D	5
1.6	Keep air usage above lower threshold of existing air tank	> 8,5 bar	R	
1.7	Not decrease LiDAR horizontal FoV	270°	R	
1.8	Should not obstruct the emitted laser pulse	0% obstruction of emitted beam	R	
1.9	Should not obstruct the receiving laser pulse	≥ 30mm vertical gap	R	
1.12	Length of cleaning sequence	< 20 sec	R	
1.13	Length of cleaning sequence	< 10 sec	D	5
1.15	No need for additional cleaning sequence	Successful cleaning in one sequence 95% of the time	D	4
1.18	Should clean the entire FoV	270°	R	
1.19	Should clean all IR-sensors	7 IR-sensors	R	
2.4	Should not damage optics cover of the LiDAR	No abrasive action	R	

5

Concept Development

This chapter aims to exhibit the progress and results obtained through the concept development phase of the thesis. The concept development phase followed the research phase, with the results of each step in the development phase working as the foundation for the next step. Certain steps of the concept development generated a lot of results, such as generated concepts, which will not be fully accounted for in the report. Some results obtained, with informational relevance for the final product, will be used as comparisons to clarify other relevant results and as proof of concept. This is done in an attempt to keep the report as concise and informative as possible for the reader.

5.1 Concept Generation

5.1.1 Functional Mapping

To support the concept generation of the LiDAR cleaning system, a functional mapping is constructed with a *Functional Means Tree*, see Figures D.1 and D.2 in Appendix D. During the mapping, the entire system is considered in order to understand the various functions involved and to not limit the potential solution space. To support the functional mapping online searches and patent searches were performed to expand the number of solutions by taking inspiration from solutions to similar problems. The primary function *Clean LiDAR sensor* is decomposed into two sub-functions, *Remove obstructions* and *Ease cleaning. Remove obstructions* is further decomposed into the sub-functions *Water-, Air-* and *Mechanical systems* as means of removing obstructions. Furthermore, as shown in orange in Figure 5.1, seven sub-functions that are in large separated from the supporting systems and consequently more connected to the primary function of *Clean LiDAR sensor* is initially chosen to be in focus. The focus enables sub-solutions with greater flexibility as they have a lesser impact on other parts of the system. For every sub-function, several sub-solutions is generated as the possible means of solving the function. The seven sub-functions are described below:

- **Distribute water/air:** The fluids are needed to be distributed to the surface of the LiDAR optics cover to remove obstructions and thereby clean the surface.

- **Direct water/air:** The fluids can be applied to the LiDAR optics cover from various directions. Several aspects are affected by the direction of the fluids. The LiDAR optics cover is tilted causing certain angles to be achievable only from one direction. Due to the shape of the LiDAR body, the accessibility around the LiDAR also differ.

- **Move distributor of water/air:** The distributors of the fluids can either be fixated, move in a horizontal or vertical plane or both.

- **Detach obstructions:** With a mechanical system, the obstructions can be detached and removed by physical means.

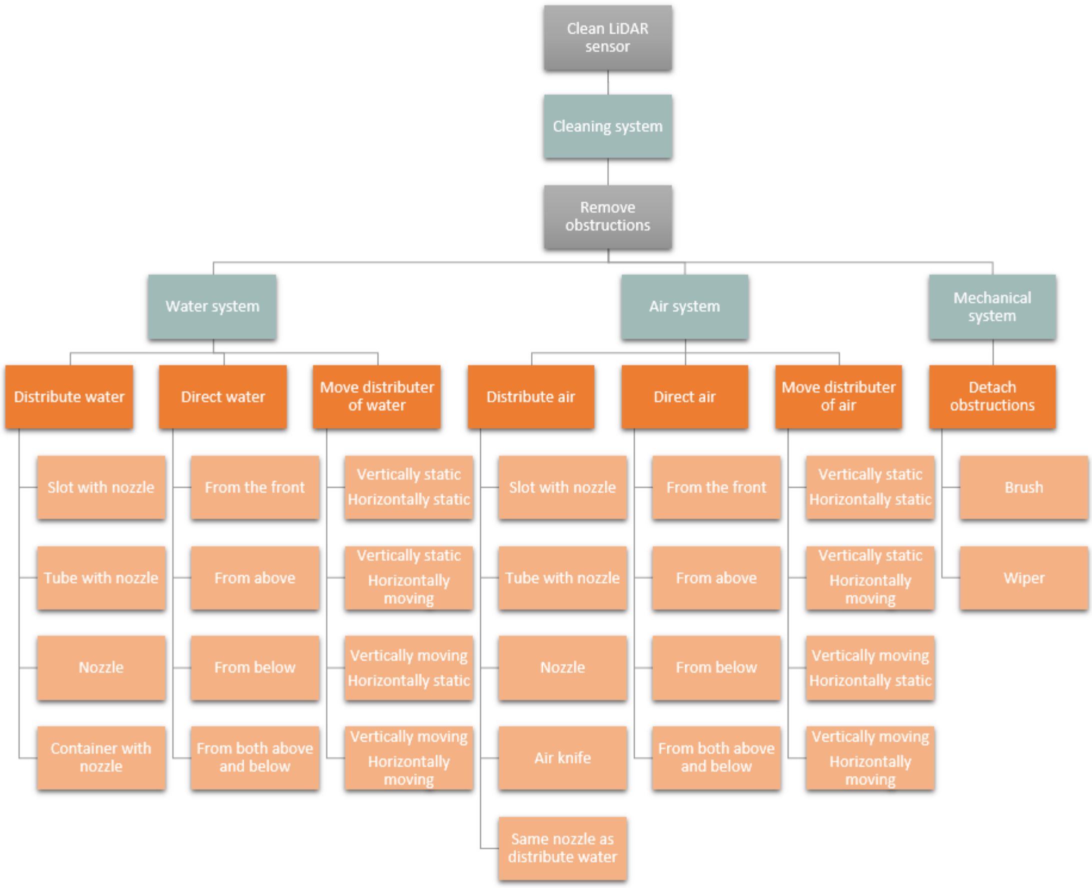


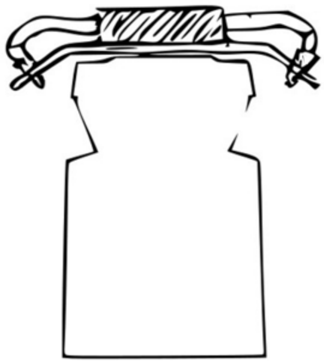
Figure 5.1: Function Means Tree of the focus area containing the seven sub-functions and their potential sub-solutions.

Although several sub-functions related to the complete system is excluded at this stage, they are still to be considered throughout the project as they impact designs of the focus area. For instance, the functions of fluids being supplied and transported need to be considered since they act as inputs to the chosen functions.

5.1.2 Generation and Description of Concepts

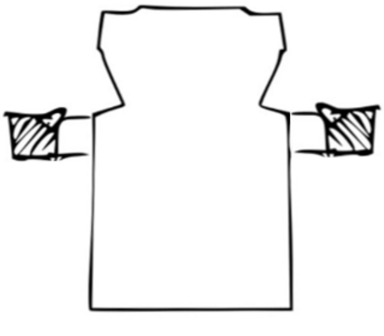
The generated sub-solutions, 27 in total, are arranged in a *Morphological Matrix* where they correspond to the seven chosen sub-functions, see Figure E.1 in Appendix

E. By combining the different sub-solutions, seven concepts of total solutions are generated. Figures E.2 to E.8 in Appendix E show the selected sub-solutions for each concept. A sketch and a short description of each concept are shown below. The number of concepts generated is sufficient to ensure that most sub-solutions are represented and therefore possible to evaluate further on.



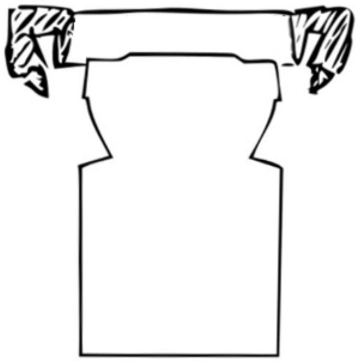
Top Plate
The concept is positioned above the LiDAR, see Figure 5.2 Hoses distribute the fluids to multiple nozzles that are mounted on a plate, shaped to direct the fluids as desired.

Figure 5.2: Sketch of concept Top Plate.



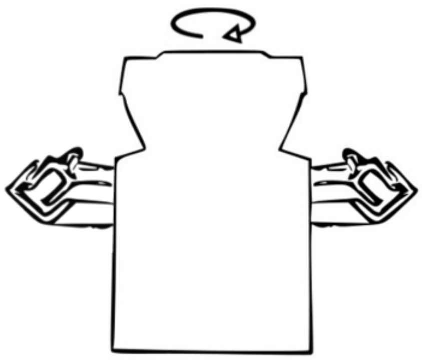
Fixed Ring Below
The concept is a fixed ring that wraps around the LiDAR to direct the fluids from below, see Figure 5.3. The fluids are distributed in the ring with slots that are connected to multiple nozzles.

Figure 5.3: Sketch of concept Fixed Ring Below.



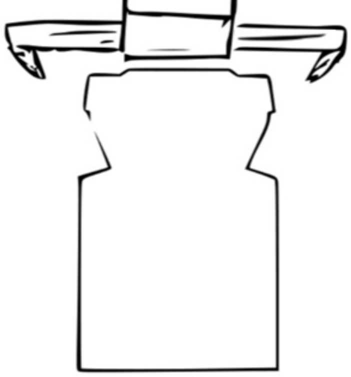
Solid Ring Above
The concept is a fixed ring that is positioned above the LiDAR to direct the fluids from above, see Figure 5.4. The water is distributed to multiple nozzles with slots. However, the air is distributed to an open slot located closer to the LiDAR to create an air knife around the edge of the LiDAR.

Figure 5.4: Sketch of concept Solid Ring Above.



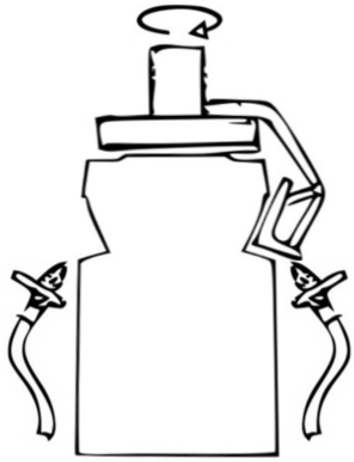
Spinning Ring
The concept is a ring that wraps around the LiDAR to direct the fluids from below, see Figure 5.5. A few nozzles are mounted to an inner ring with blades that rotates by the flow of the fluids.

Figure 5.5: Sketch of concept Spinning Ring.



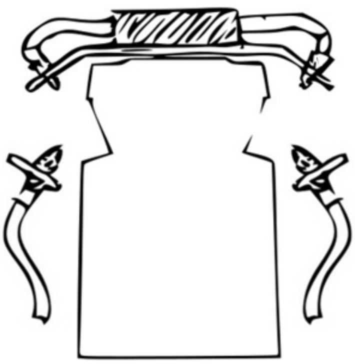
Spinner
The concept consists of two arms positioned above the LiDAR, see Figure 5.6. A nozzle to distribute the fluids is mounted at the end of each arm. Furthermore, the arms are rotated by the flow of the fluids.

Figure 5.6: Sketch of concept Spinner.



Wiper
In the concept, a wiper is positioned above the LiDAR to wipe the optics cover and shelf, see Figure 5.7. A motor at the top rotates the wiper 360°. Multiple nozzles are mounted to a plate to distribute the fluids from below.

Figure 5.7: Sketch of concept Wiper.



The Clash
The concept's water distribution is positioned above the LiDAR, similar to concept *Top Plate*, see Figure 5.8. However, the air distribution is performed from below with separate nozzles that are mounted on a plate.

Figure 5.8: Sketch of concept The Clash.

5.2 Concept Evaluation and Selection

5.2.1 Elimination of Concepts

The generated concepts are initially screened in a *Elimination Matrix* to exclude any concept that does not fulfill the criteria set up in the matrix. The eight screening criteria encompass among others; that the concept solves the main problem, fulfills the requirements and is feasible to develop within reasonable cost and within the project scope.

Six out of the seven concepts passes the screening and will continue to be further evaluated. However, concept *Spinning Ring* is eliminated due to not fulfilling all requirements. The concept is designed as a spinning ring that is rotated by the force from the fluid flow. The design is assessed to use high amounts of cleaning fluid to drive the rotating mechanism. Furthermore, the concept deemed as not being space efficient and adding unnecessary complexity that makes it of a high risk of not fulfilling additional requirements and not being feasible. The criteria and result of the screening is shown in Figure 5.9.

Elimination Matrix

Development of a LiDAR Cleaning System for Autonomous Trucks

Elimination criteria:
- Pass concept (grey hatching)
- Eliminate concept (orange hatching)
- (?) Search for more information
- (!) Check requirement specification

Concepts	Solves main problem	Fulfills all requirements	Feasibility	Reasonable cost	Safe (Human/Societal)	Fits pilot project scope	Compatible with current system	Enough information	Decisions
Top Plate	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Passed
Fixed Ring Below	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Passed
Solid Ring Above	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Passed
Spinning Ring	Pass	Eliminate							Eliminated
Spinner	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Passed
Wiper	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Passed
The Clash	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Passed

Figure 5.9: Elimination Matrix.

5.2.2 Selection of Concept

The concepts are evaluated in a *Pugh Concept Selection Matrix* to compare their performance regarding 18 criteria based on requirements and desires. The criteria are categorized into three groups; Cleaning, Production and Maintenance as well as Miscellaneous, see Figure 5.10. Concept *Top Plate* is established as the reference in the evaluation.

An explanation of each criteria applied in the *Pugh Concept Selection Matrix* is presented below.

- **Water and air usage:** The amount of fluid that is used during the cleaning process are limited resources. Furthermore, multiple simultaneous LiDAR cleaning is only possible with low resource usage as the supply of fluids by supporting systems is restricted.
- **Length of cleaning sequence:** The time it takes to perform the cleaning. The possibility of a shorter cleaning sequence increases the up-time and flexibility of the cleaning and drying.
- **Risk of additional cleaning sequence:** Predictable cleaning performance reduces the risk of additional cleaning.
- **Clean optics cover and IR-sensors:** The coverage of the cleaning to ensure the needed surfaces are cleaned.
- **Risk of removed obstructions re-emerging:** Risks of deposits that con-

tain fluids or dirt that re-emerges.

- **Risk of damaging optics cover:** The optics cover is resistant to a degree, however, there is a risk of abrasion from certain forms of cleaning.
- **Cleaning reliability:** The cleaning system's reliability to function as designed over time due to wear.
- **Ease of changing parts and system maintenance:** The accessibility and ease of changing parts to clean and maintain the cleaning system.
- **Assembly and installation:** The total time of assembly and installation should be kept low. Reduced complexity is achieved with fewer and easier steps during the process of assembly and installation.
- **Production:** The available manufacturing methods affects the flexibility, time and cost of the production.
- **Number of parts:** In general, fewer parts is desired as it reduces complexity and lowers costs during the whole product life cycle.
- **Environmental robustness:** The ability to withstand temperature and precipitation.
- **Robust against change:** The development of LiDAR technology is rapid, changing the dimensions, shapes and performance of LiDARs. Adaptability to these changes is crucial to prevent the cleaning system from becoming obsolete.
- **Ability to Utilize Volvo's existing products:** Standard parts, especially those already in use at Volvo is preferred as they are tested and proven already.
- **Product development complexity:** The complexity of the product development is affected by the difficulty of optimizing the concept as well as adding complementary systems.

Pugh Concept Selection

Development of a LiDAR Cleaning System for Autonomous Trucks

	Criteria	Top Plate	Fixed Ring Below	Solid Ring Above	Spinner	Wiper	The Clash
Cleaning	Water usage	REFERENCE	▬	▬	▲	▲	▬
	Air usage		▬	▲	▲	▲	▲
	Length of cleaning sequence		▬	▲	▼	▲	▲
	Risk of additional cleaning sequence		▬	▲	▬	▼	▲
	Clean optical window		▬	▬	▲	▲	▬
	Clean IR-sensors		▼	▬	▲	▲	▬
	Risk of removed obstuctions re-emerging		▼	▬	▬	▼	▼
	Risk of damageing optical window		▬	▬	▬	▼	▬
	Cleaning reliability		▬	▬	▼	▼	▬
Production and maintenance	Ease of changing parts		▼	▬	▼	▼	▼
	Ease of system maintenance		▬	▬	▼	▼	▬
	Assembly and installation		▲	▲	▼	▼	▼
	Production		▼	▼	▼	▼	▼
	Number of parts		▲	▲	▲	▼	▼
Miscellaneous	Enviromental robustness		▼	▬	▼	▼	▼
	Robust against change		▬	▬	▬	▼	▬
	Ability to utilize Volvo's existing products		▼	▼	▼	▼	▬
	Product development complexity		▬	▼	▼	▼	▬
Result	Number of positives		2	5	5	5	3
	Number of neutrals		10	10	4	0	9
	Number of negatives		6	3	9	13	6
	Total value		-4	2	-4	-8	-3
	Rank	2	4	1	4	5	3

Figure 5.10: Pugh Concept Selection Matrix.

Table 5.1: List of advantages and disadvantages of the concepts.

Advantages	Disadvantages
Top Plate	
Overall simplicity, easy to develop	Same nozzle for water and air, water drops in airstream
Everything in the hat, geometrical freedom	Poor nozzle position
Simple production method, sheet metal and standard parts	
Water and air from the above, potentially better for cleaning of shelf	
Uses standard components to a large extent	
Fixed Ring Below	
Integrated, can act as a structural element in the helmet	Poor cleaning of shelf
Few parts	Production of a large complex solid ring
Inherits positives of "hat-solutions" if lidar is flipped	
Solid Ring Above	
Separates air and water	Production of a large complex solid ring
Fluid specific nozzle	Difficulty of developing own designed air knife, few standard parts
More efficient air usage	Potentially tight on space in the hat
Everything in the hat, geometrical freedom	
Spinner	
Good coverage with few nozzles	Possibly long cleaning sequence
Low fluid consumption	Moving parts, uncertainty on how well the air rotates the spinner
	Development complexity due to bearings, axles
	Few standard parts
	Same nozzle for water and air
Wiper	
Three methods of cleaning	Risk of abrasion
Might need less fluid	Moving parts
Good coverage	Development complexity due to bearings, axles and electrical system
	Few standard parts
	More sensitive to environmental aspects
The Clash	
Separates air and water	Possibility for the water to transfer the dirt up in the hat and then re-emerging
Fluid specific nozzle to highest efficiency	Affects both the hat and helmet design, larger design space
Compact design with fluid specific nozzles	Harder to change and service parts
Simple production method, sheet metal and standard parts	Many parts
Uses standard components to a large extent	

The evaluation demonstrate that concept *Top Plate* and *Solid Ring Above* performed better compared to the other concepts. Both concepts lack any significant weak points, however, they do not distinguish themselves in any specific area of performance either. The primary reasons for marking the concepts in the *Pugh Concept Selection Matrix* are compiled as advantages and disadvantages, see Table 5.1.

The concepts involving rotating mechanisms, *Spinner* and *Wiper*, perform poorly in the evaluation. Their weakness is their inherent complexity and difficulty to attain the required reliability. The two concepts are classified as too uncertain and are consequently dismissed as concepts to develop further. To improve the performance of the remaining concepts, an assessment of is made potential changes to improve the concepts and counteract the disadvantages while enhancing the advantages to increase the overall ability of the concept. In general, it was recognized that separating the fluids into different channels is beneficial to achieve the best performance and efficiency of the cleaning. This was due to that in the previous cleaning system, water residuals remained in the channels and were distributed during the air-phase of the cleaning cycle. This led to a less efficient drying phase in the cleaning sequence. Furthermore, the direction of both fluids is preferred to be coming from above. This ensures the best accessibility of the LiDAR optics cover as well as the shelf on which the IR-sensors measuring the obstruction-levels are located. By having all fluid distribution from above, it is also possible to increase the compactness and the design freedom of the cleaning system. By implementing these changes to all concepts, *Fixed Ring Below* and *The Clash* become very similar to the top-performing concepts making them unnecessary.

A combination of *Top Plate* and *Solid Ring Above* creates a new concept, *Top Plate Block*, see Figure 5.11 and E.9 in Appendix E. The air nozzles are mounted on a block that distributes the air in slots while the water is distributed with hoses. An updated version of *Solid Ring Above* creates another concept, *Top Block*, see Figure 5.12 and E.10 in Appendix E. In this concept, both types of fluids are distributed in slots making the distribution block to also function as the mounting point for all nozzles. In both new concepts, the air knife sub-solution is kept. However, the function is changed to be accomplished by several nozzles that when placed close together acts as a uniform air knife.

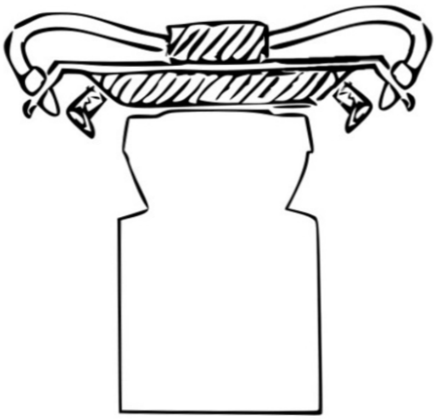


Figure 5.11: Sketch of concept Top Plate Block.

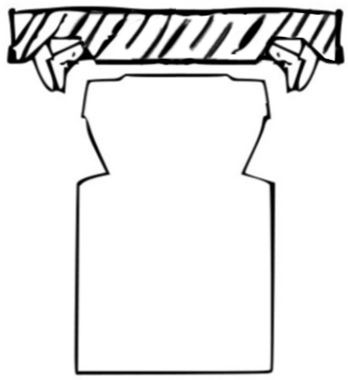


Figure 5.12: Sketch of concept Top Block.

Throughout the concept generation and selection phase, the concepts were modeled in 3D along with the LiDAR helmet and LiDAR to better understand the geometrical advantages and disadvantages of each concept. This work led to the group having the ability to in better detail compare concepts and understand where improvements could be made and how different changes in design parameters affected the surrounding components and systems. During this process, it emerged that *Top Plate Block* added previously overlooked complexity and required larger geometrical dimensions to be realized. The use of hoses to the nozzles for water distribution positioned with sheet metal parts is the main weakness. To connect all nozzles to hoses, several couplings and adapters are needed. When considering that multiple short hoses, couplings and adapters are needed for each nozzle, the number of interfaces increases drastically. It is problematic as the space available is limited and the numerous interfaces reduce reliability and increase the difficulty of assembling. Concept *Top Block's* design lacks these shortcomings. The block design functions as a distributor for both water and air as well as mounting points for all nozzles, eliminating the need for unnecessary interfaces.

It was decided to not perform an iteration of the *Pugh Concept Selection Matrix* with the updated and additional concepts. The limitations set on the thesis design space, the need to increase detail in the design of the concepts and the time needed to design and produce the prototype were the primary reasons. Accordingly, concept *Top Block* is selected as the concept to further develop and evaluate.

6
Design of Cleaning Head

This chapter aims to exhibit the progress and results obtained through the design development phase of the thesis. It starts with the development of the design that enables fluid distribution. The section is followed by the selection of nozzles and their coverage. The chapter ends with two variants of the prototype being described and evaluated in simulations.

6.1 Design of Fluid Distribution

Following the concept selection, compliance between the conceptual cleaning system and the existing systems of the truck were considered in the design of the cleaning head. Extensive contact with suppliers of components during the development ensures that the cleaning system satisfies the requirements of the external components. This was important in order to achieve full functionality and performance of the outsourced components. Due to long lead times in contact with suppliers and personnel at Volvo, the decision was taken to deviate from the intended workflow, see Section 2.1. A concurrent engineering approach in the work with *System-level Design* and *Detail Design* was taken to speed up the design process.

At this stage, the vision was to develop a design that had multiple possibilities of manufacturing. It enables focus on the functionality of the cleaning head while not limiting the possibilities of producing the prototype. The desired functionality of the cleaning head could be achieved by milling the cleaning head in aluminium. Multiple iterations of designs with this manufacturing method in mind were evaluated. In this design-phase, the set desires and requirements continued to dictate the design together with further geometrical assurance by 3D modeling. The design of the cleaning head proceeds from concept *Top Block*. Henceforth, concept *Top Block* is named *Divided Prototype*.

The cleaning head is divided into two parts and therefore named the *Divided Prototype*, shown in Figure 6.1. In the cleaning head, six positions for water nozzles and seven positions for air nozzles are incorporated, see Figure 6.2. When splitting the block in two, the slots that distribute the fluids are incorporated in one of the parts while the other works as a lid. With milling as the manufacturing method, a cleaning head in a single block is possible to design and manufacture. However, such a distribution block requires the channels to be in the form of drill holes that intersect and are plugged in places. Moreover, the method is limiting when designing as the drill holes are straight and interfere with each other causing the block to increase in dimensions. Instead, the size of the cleaning head is minimized by combining drill holes and slots. The material utilization is high and the complex geometry is able to be kept to one of the two parts, partly by placing the fluid inlets at the top. The total height of the cleaning head ads up to 33 mm and the diameter is 184 mm. There are twelve holes in the lid part with corresponding holes threaded for M5 screws in the part with the slots. These screws both join the parts together and allows the cleaning head to be mounted in a test rig.

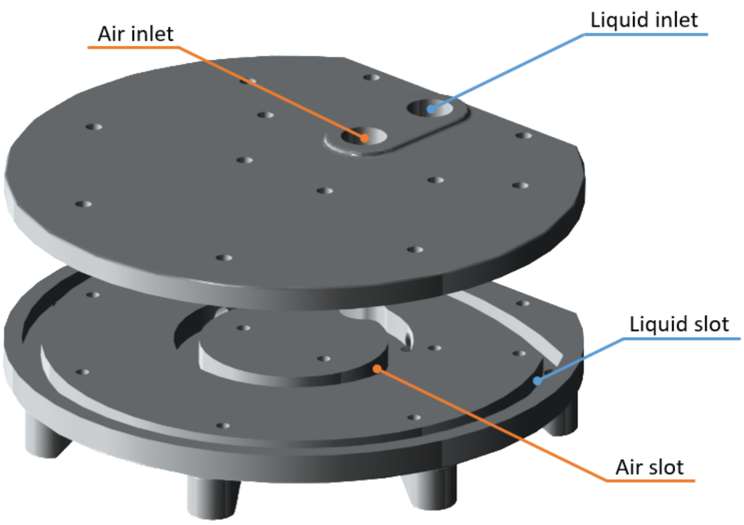


Figure 6.1: Design of the Divided Prototype shown in an exploded view, seen from above.

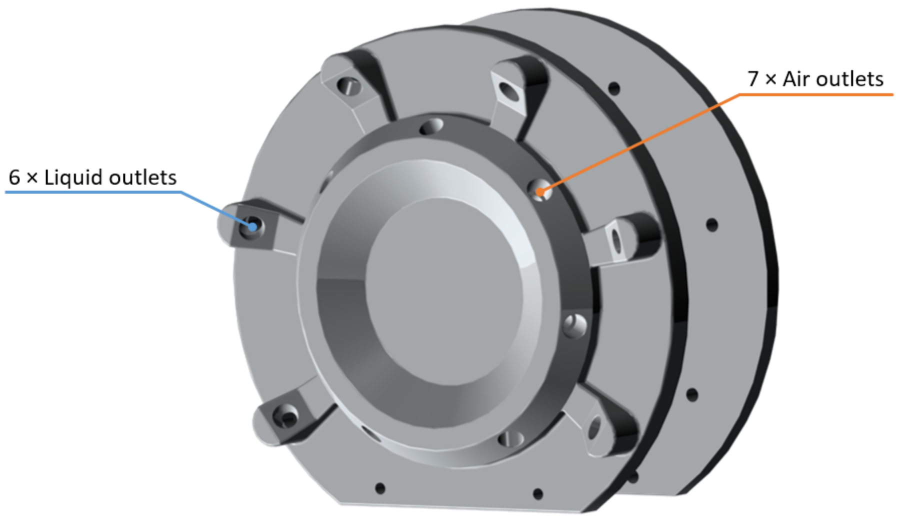


Figure 6.2: Design of the Divided Prototype shown in an exploded view, seen from below.

To dimension the two fluid inlets, the expertise of the nozzle manufactures was utilized. By following their recommendations, the inlets were determined to accommodate couplings of 3/8" ($9,525$ mm) for the cleaning fluid and 1/2" ($12,7$ mm) for the compressed air. The cross-sectional area for the fluids is maintained in the slots that connect the nozzles in series. The inlets, outlets and the slots of *Divided Prototype* are visualized in Figure 6.3.

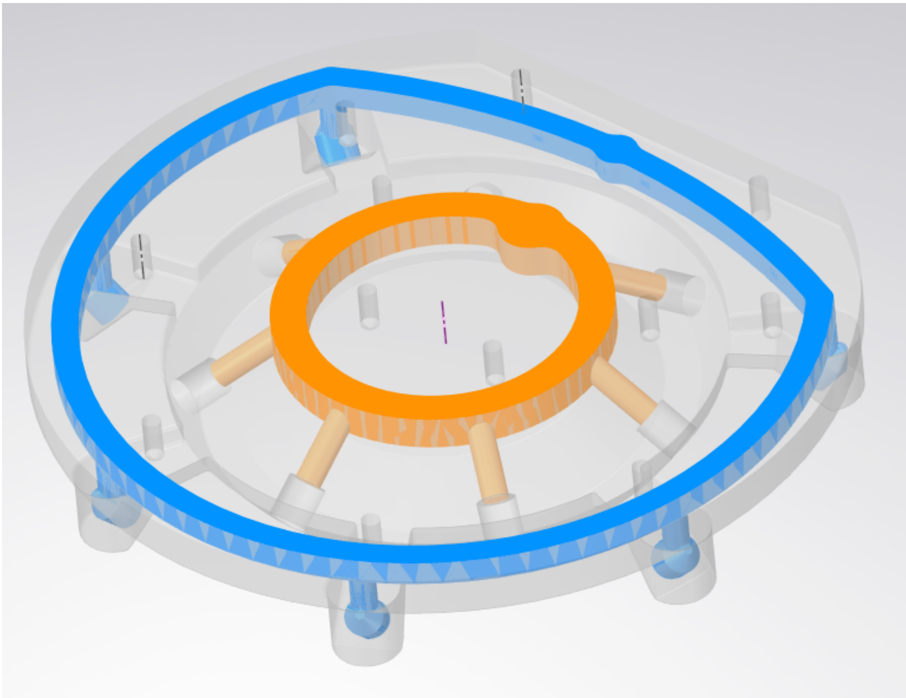


Figure 6.3: Visualization of the slots for liquid and air distribution. The liquid is shown in blue (outer slot), while the air is shown in orange (inner slot).

The couplings and hoses widely used on Volvo's trucks are of the metric standard. It was therefore beneficial to use this standard on the cleaning head to the largest extent possible. The inlets were dimensioned to allow for couplings with a male M16. This in turn allowed for couplings that could accommodate hoses with an outer diameter between 8 and 16 mm increasing the flexibility by allowing testing of various hose dimensions, see Figure 6.4. Table 6.1 shows the corresponding inner diameter of the different hoses. The outlets for the nozzles are all female threaded to British Standard Pipe Parallel (BSPP). This enables the outlet to mount both parallel and tapered male threaded nozzles [36]. As the nozzles are mounted with treads, the design had to ensure that the nozzles had enough space to be screwed into the cleaning head.

Table 6.1: Dimensions of the different metric hoses.

Hose Outer Diameter [mm]	**Hose Inner Diameter [mm]**
8	6
12	9
16	12

Figure 6.4: M16 couplings for the hose sizes of 16, 12 and 8 mm.

6.2 Selection of Nozzles

To achieve high efficiency of the fluids distributed by the cleaning head, it is decided to use fluid specific nozzles. Air nozzles are used to manage and direct the compressed air by reducing turbulence. The nozzles increase efficiency while also producing an air stream with more force [37]. *Silvent 961* air nozzles, see Figure 6.5, are selected to distribute the compressed air. The nozzle produces a flat blow pattern similar to an air knife, especially when positioned in an array with several nozzles close together. The blow angle is 90° relative to the male G 1/8” connection [38]. The G thread type is also referred to as BSPP-thread [36]. This enables the nozzles to be mounted closer to the center enabling a more compact design while still achieving the desired blow direction and angle. When mounted, the nozzle protrudes $15,5$ mm from the mounting surface and the width of the strip with the multiple orifices is $23,9$ mm [38].

Figure 6.5: Silvent 961 air nozzle.

The maximum operating pressure of the nozzles is 10 bar. The flow rate and blow force at different pressures are plotted in Figure 6.6. The chart shows that the flow rate and blow force increases at the same rate with raised pressure. The distance between the shelf and the nozzles is approximately 50 mm with a lesser distance to the optics cover. The width and height of the blow pattern at a distance of 50 mm is 35 mm and 25 mm respectively, see Figure 6.7 [38].

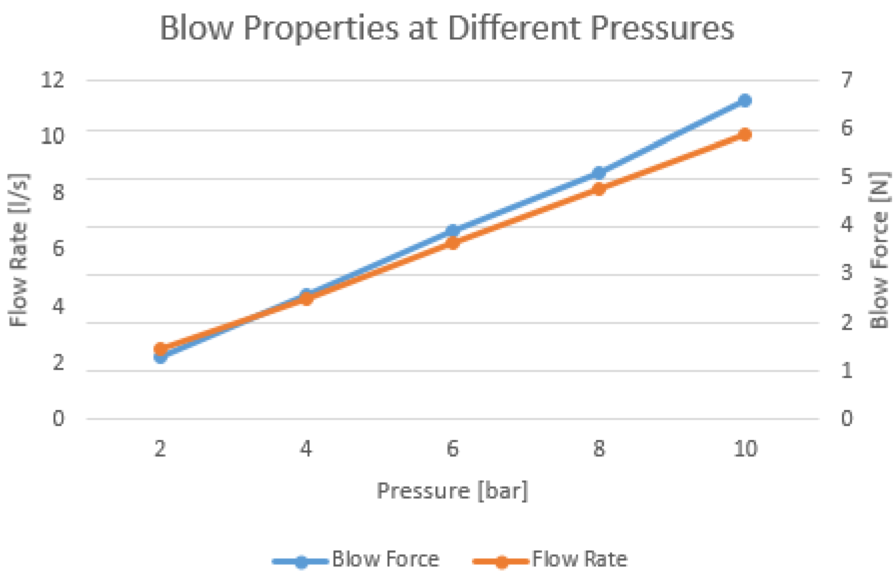


Figure 6.6: Blow properties of Silvent 961 air nozzle.

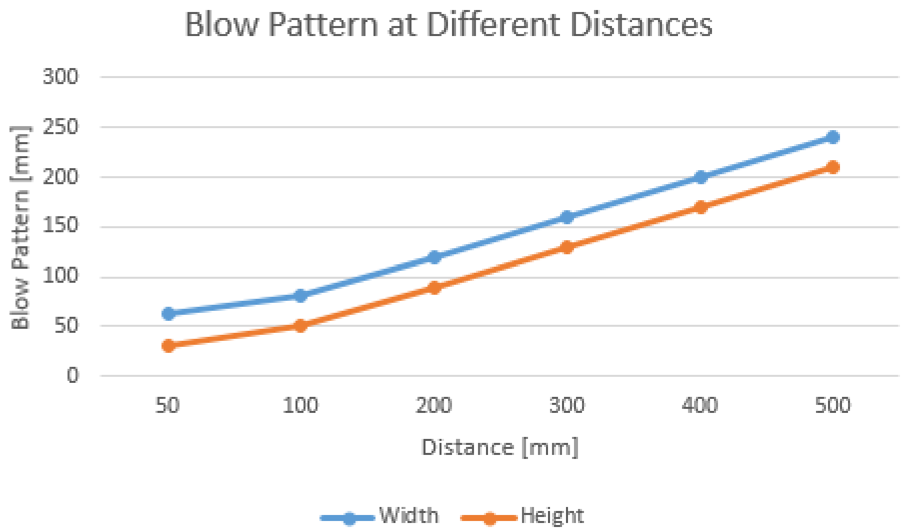


Figure 6.7: Blow pattern of Silvent 961 air nozzle. Scaling of the distance is not consistent.

Full Cone water nozzles are chosen to ensure full wetting of the surface in need of cleaning. The good coverage of *Full Cone* nozzles is believed to be beneficial because a large surface area is possible to clean without an excessive amount of nozzles or moving mechanics. The selected water spray nozzles are *Spraying Systems' B1/8HH*, see Figure 6.8. The nozzle generates a *Full Cone* pattern with a spray angle of 58° at 1,5 bar and a slightly narrower angle at higher pressures, 53° at 6 bar. In contrast to the air nozzle, the water spray nozzle is not angled 90° as angled water spray nozzle designs generally are unavailable with low flow rates. The same is true for nozzles with wider spray angles. The flow rate at different pressures is illustrated in Figure 6.9 [39]. The small dimensions, 12,7 mm in diameter and a protrusion of 15,6 mm when mounted, give the nozzle a compact design. The male connection is of the thread type R 1/8" [39], also referred to as British Standard Pipe Tapered (BSPT) [36].

Figure 6.8: Spraying Systems' B1/8HH spray nozzle

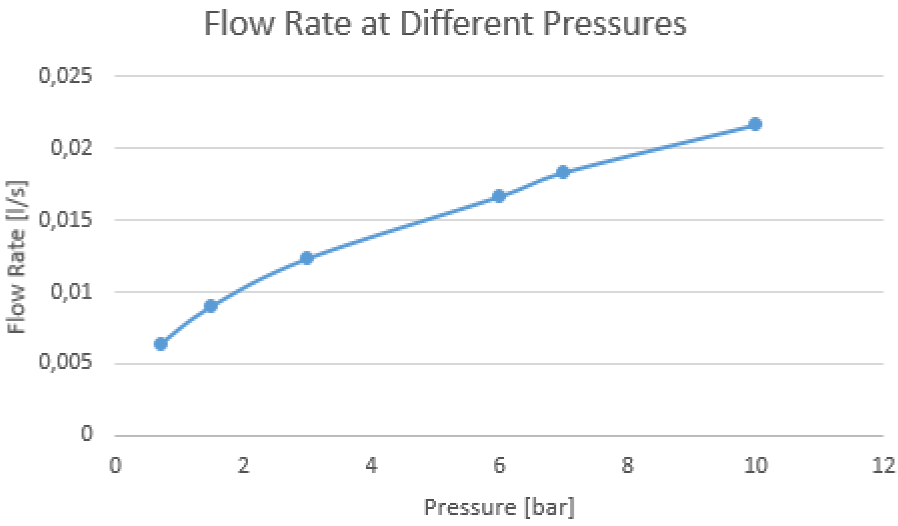


Figure 6.9: Flow rate at different pressures with Spraying Systems' B1/8HH spray nozzle.

6.3 Spray and Blow Coverage

The water spray nozzles are positioned to obtain the desired coverage with as few nozzles as possible. Both the optics cover and the shelf containing the seven IR-sensors are required to be cleaned. This is achieved by distributing the cleaning fluid from an angle that hits both surfaces and partially neglect the rear facing 90° of the optics cover, see Figure 6.10. In order to restrain the usage of cleaning fluid, complete theoretical coverage is not assumed to be optimal. The cleaning liquid will disperse at impact increasing the coverage. In addition, complete theoretical coverage would clean unnecessary surfaces leading to waste in the cleaning process.

Figure 6.10: Theoretical spray pattern projected with five B1/8HH nozzles with a spray angle of 53°, evenly positioned over 216°.

The air knife characteristics of the selected air nozzles will create a precise and powerful air curtain that will act in two stages. Firstly, it will help to remove the wetted dirt on the optics cover. Secondly, it will dry the optics cover from moisture that remains after the dirt is removed. The coverage of the air nozzles is designed to be more extensive than that of the water spray nozzles, drying potential water that flowed towards the back of the LiDAR during the water application of the cleaning sequence. The air nozzles are positioned to blow a curtain of air along with the optics cover and thereby transfer remaining dirt and cleaning fluid in one direction. Furthermore, the air stream is also directed to dry the shelf, see Figure 6.11.

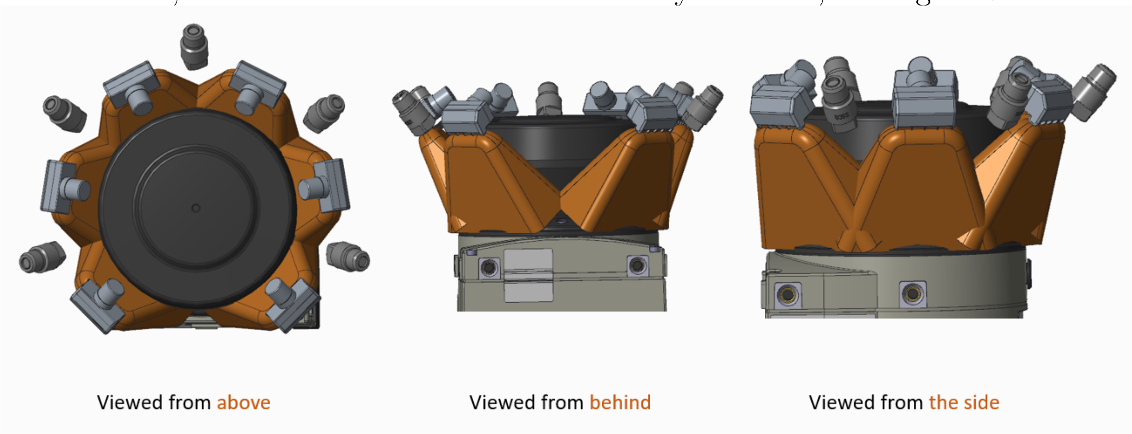


Figure 6.11: Theoretical blow pattern projected with six Silvent 961 nozzles, evenly positioned over 270°.

The position of the nozzles in relation to the LiDAR is shown in Figure 6.12. These angles and distances are used as the original placement of the nozzles of which the testing in Section 7.5.1 refers to. The nozzles, which corresponds to the lowest part of the cleaning head, have an approximately distance of 30 mm to the center line of the optics cover. As stated in the *Specification of Requirements*, criteria 1.8 and 1.9 requires a minimum vertical gap of 15 mm in both directions of the center line. The placement of the cleaning head and its nozzles is well within the requirements. Moreover, the LiDAR's horizontal FOV is not obstructed which the criteria 1.7 requires.

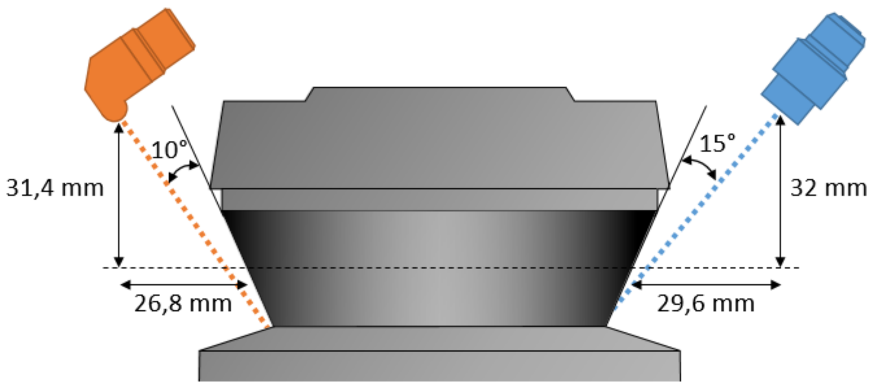


Figure 6.12: The placement of the nozzles' orifices in relation to the centerline of the optics cover and the angle of the nozzle in relation to the surface of the optics cover. The air and water nozzle are illustrated in orange and blue respectively

6.4 Variants of the Prototype

The cost of milling the two parts of the *Divided Prototype* in aluminium at an external manufacturer was 21000 SEK. Furthermore, the manufacturer reported that the design was possible to mill. To enable prototyping with shorter lead times at relatively low cost, in comparison with milling aluminium, SLS 3D printing of the prototype in PA 12 was considered. SLS is frequently used at Volvo for prototyping components and the printing is available in-house. With the lower costs and increased flexibility, both *Divided Prototype* and an additional variant could be manufactured. The newly established variant called *Solid Prototype* has five positions for water nozzles and six positions for air nozzles, see Figure 6.13.

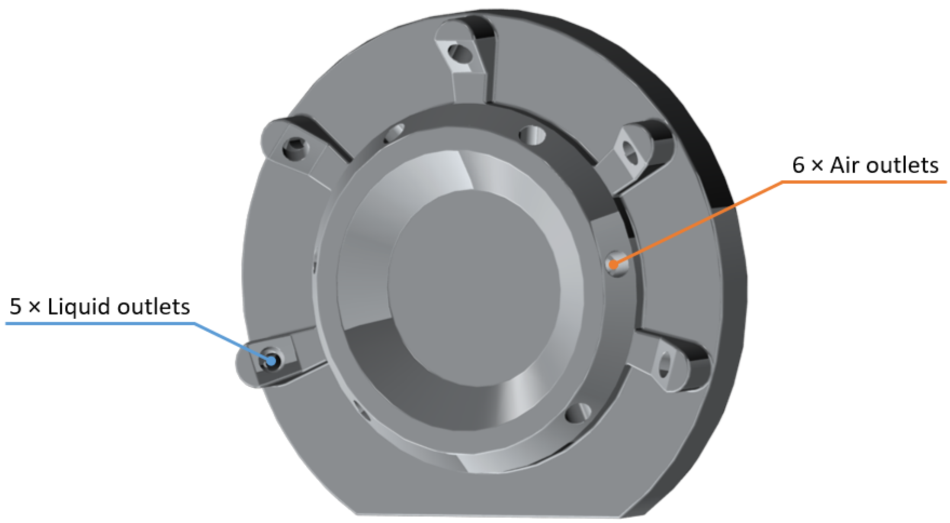


Figure 6.13: Design of the Solid Prototype, seen from below.

The coverage of this configuration is previously illustrated in Section 6.3. Even though the rear facing 90° of the optics cover is not used by the LiDAR as the scanning range is 270°, the *Divided Prototype* has increased coverage due to the extra nozzles. Dirt and cleaning fluid that might gather on this part of the optics cover could possibly be displaced, not least when the vehicle is moving, to a cleaned area. It is a potential trade-off, where better coverage with additional nozzles might solve this issue. However, with higher resource usage as a consequence.

There were uncertainties in how to remove the residual powder in the channels. Thereof, only *Solid Prototype* was 3D printed as one part which its name entails. To further support the investigation of the material and technology, see Section 3.7. To see if it would suffice for testing purposes, structural simulations were performed on the intended design. For the structural simulations the simulation software *ANSYS* was used, see Section 2.3.2. The simulations were performed as *static structural* simulations where the planned attachment point of the cleaning head to the helmet was modeled as fixed supports. The internal channels were assigned an internal pressure of 10 bar. The threaded surfaces for the water nozzles are assigned with distributed forces. The forces of 5 N normal to the direction of the water spray simulates the force that the water spray creates. The prototype was given the material properties of PA 12, see 3.1. The outputs of the simulations were total deformation and equivalent stress. The results of deformation simulations for the *Solid Prototype* can be seen in Figure 6.14 and Figure 6.15. The results of stress simulations for the *Solid Prototype* can be seen in Figures 6.16 and 6.17.

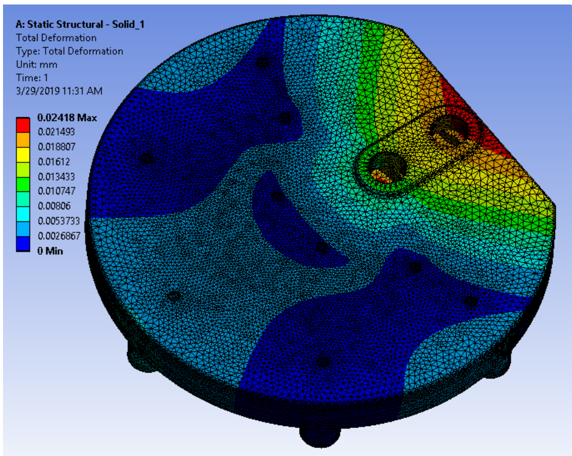


Figure 6.14: Total deformation simulation of *Solid Prototype*. Seen from above.

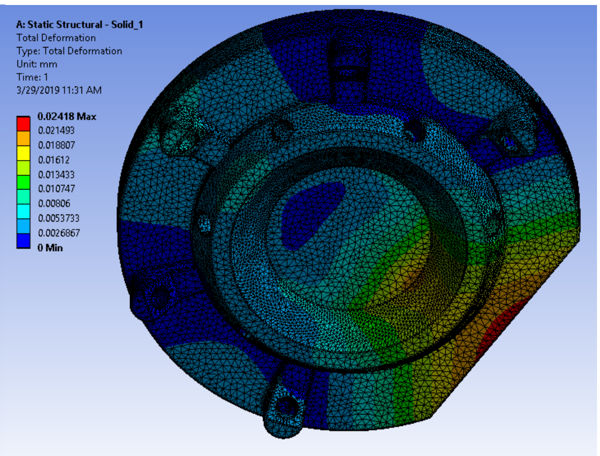


Figure 6.15: Total deformation simulation of *Solid Prototype*. Seen from below.

The results of the deformation simulation showed that the maximum total deformation of the *Solid Prototype* is approximately $0,0242$ mm. The deformation occurs at the back of the prototype, probably due to the two fluids flowing from the inlets having a 90° to the channels. This deformation is considered to be within the boundaries of the design. The reason is that the small deformation does not significantly alter the angles of the nozzles in reference to the LiDAR.

The result of the stress simulations showed that the maximum stress occurs in the inner channel, shown in Figure 6.16 and Figure 6.17 by the red "Max" marker. The maximum stress of approximately $4,85$ MPa occurs at the junction between the channels and the outlets. In other parts of the , it can be seen that relatively low stresses occur. The stress levels of the model in relation to the material properties of PA 12, see Table 3.1 in Section 3.7, are considered low.

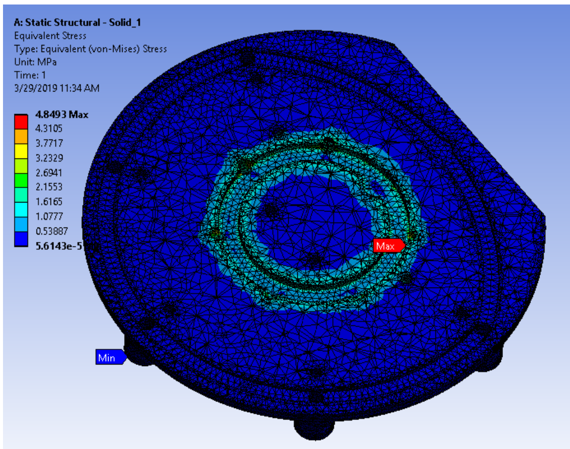


Figure 6.16: Equivalent stress for *Solid Prototype*. Seen in cross section from above.

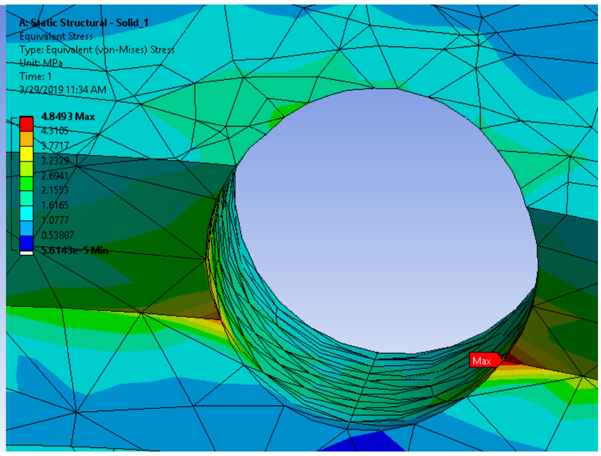


Figure 6.17: Maximum equivalent stress for *Solid Prototype*. Seen in cross section from above.

From the deformation and equivalent stress simulations, it is concluded that the design of the prototype and the manufacturing method is viable for testing purposes. One of the two variants of the prototype to be further tested, *Divided Prototype*, is shown in Figures 6.18 and 6.19 assembled with screws, nozzles and couplings. The *Solid Prototype* was assembled in the same manner for testing.

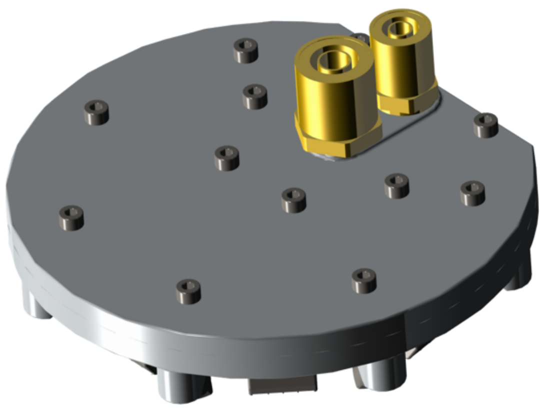


Figure 6.18: Divided Prototype assembled, seen from above.

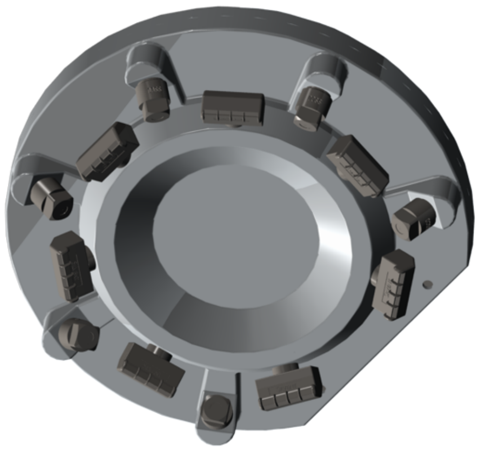


Figure 6.19: Divided Prototype assembled, seen from below.

7
Testing and Evaluation

This chapter aims to provide the reader with information about the testing of the prototypes within this thesis work. The chapter begins with an explanation of the test setup's design and limitations. The chapter continues with tests to performed to gain knowledge about the physical prototypes and the test rig. The following sections regard the individual tests and comparisons, providing the reader with in-depth information on the results provided by the tests.

7.1 Test Setup

Before starting the tests, a *Test Plan* was developed to ensure that the wanted aspects were tested and evaluated. The *Test Plan* supported in organizing the proceedings in the tests and the test process in large. The *Test Plan* also functioned as support when sourcing material, searching test facility and communicating the planned process to others of interest.

7.1.1 Test Rig Setup

The tests within this thesis work were conducted in the dirt laboratory in A-hallen at Volvo GTT in Lundby. To support the prototype and the LiDAR a frame system was built in the laboratory. The intention of the frame system design was to achieve a modular rig, allowing for quick changes in parameter setup while maintaining structural rigidity.

The frame system was constructed with aluminium profiles. The slots in the aluminium profiles allowed for flexible fastening options of components that were to be tested in the rig. The base consisted of a horizontal frame on lockable wheels. This gave the frame system good mobility and spread out the contact points with the ground making the frame system insensitive to horizontal loads. On the horizontal frame, a vertical frame was attached. On the vertical frame, two horizontal frame elements were mounted. These frame elements acted as supports for mounting the cleaning heads and the LiDAR. The elements were individually adjustable allowing for quick changes in height from the floor and the distance between the cleaning head and the LiDAR. The frame system also allowed for fastening of hoses reducing the risks during testing. The frame system used during the testing can be seen in Figure 7.1. The LiDAR was fastened to the lower horizontal frame element by a system of brackets, see Figure 7.2. The brackets were fastened with T-nuts positioned in the T-slots of the aluminium profiles. This allowed for easy sideways adjustment of the LiDAR. Slots in the brackets allowed for forward and backward adjustment of the LiDAR. The cleaning head was fastened with two brackets in the T-nuts in the T-slots on the upper horizontal frame element. The T-nuts allowed for sideways adjustment of the cleaning head, see Figure 7.2.

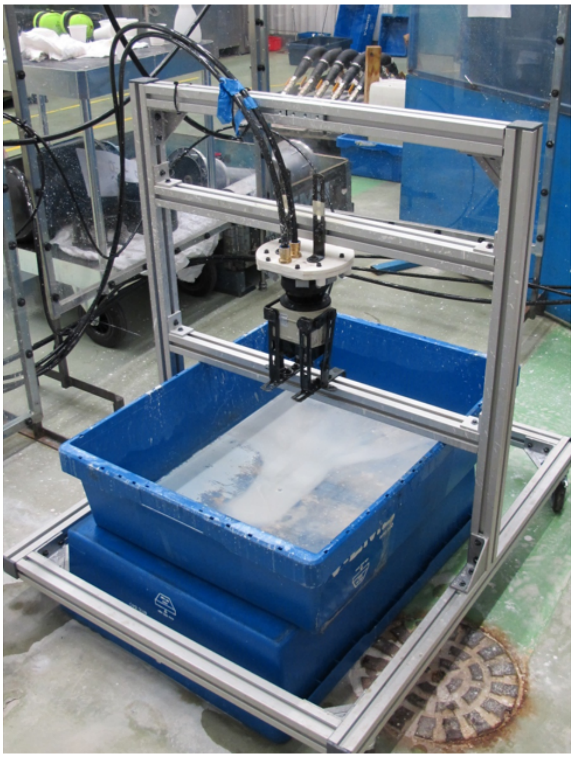


Figure 7.1: The test rig with frame, LiDAR, cleaning head and hoses installed seen from the back.

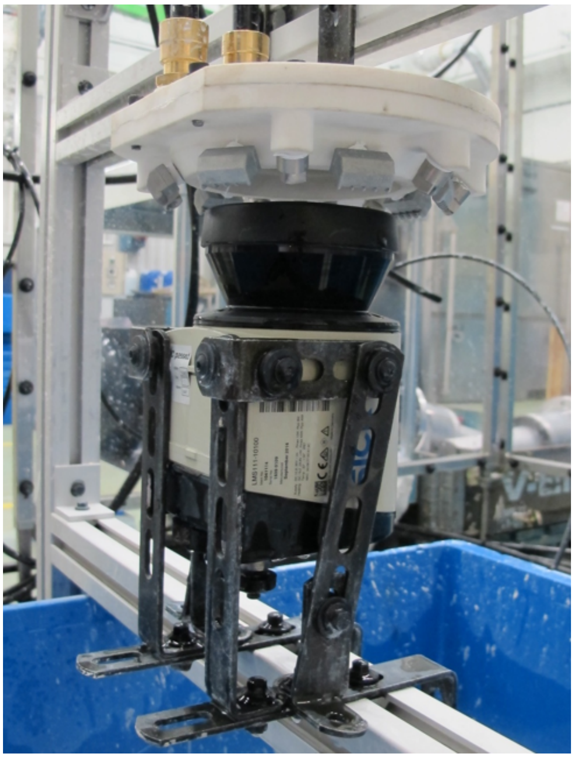


Figure 7.2: Fastened LiDAR and cleaning head on the horizontal frame elements attached to vertical frame.

The rig was placed in close proximity to a built-in air supply of the laboratory. The in-house air system has the capacity of delivering $0 - 12,5$ bar. The liquids used in the cleaning heads during testing were pressurized with compressed air in a tank of 25 liter. The tank was filled up with the liquid and connected at the top to the laboratory's air supply. At the bottom, the hose with the correct dimension for the testing was attached.

Since many risk factors were present during testing, such as relatively high pressures and high noise levels, a risk analysis was made for the test rig. For each risk factor, corrective actions were taken. For instance, protective screens were placed around the test area and hearing protection was used. The planning of the rig setup was done in collaboration with the laboratory safety representative and approved by the safety representative and the laboratory supervisor.

7.1.2 Prototype Setup

The residual powder inside the prototypes from the 3D printing, see Section 3.7, was removed from the inside channels using an air compressor blow gun. The prototypes holes were threaded with threading tools of the different holes corresponding thread size. Brackets were mounted on the prototypes for easy attachment to the frame system, see Figure 7.1. Due to manual assembly and uncertainty regarding the structural stability of the PA 12 threads, absolute correlation with the modeled protrusion, see Section 6.2 of the air nozzles cannot be guaranteed. Depending on the hose dimensioned tested, the corresponding M16 coupling for attaching the hoses were installed in the inlets.

7.1.3 Dirt Mixtures and Fluids

After consultation with personnel in the laboratory two materials were chosen to be used to simulate the dirt present at the project site. To achieve dirt mixtures, *Arizona Dust* was chosen as one ingredient as it contains multiple substances. The *Arizona Dust* particle size distribution corresponds to A4 Coarse, tested according to ISO 12103-1. The density of the dust is between $2,5 - 2,7\ g/cm^3$. The quantity of the different components included in the dust is shown in Table 7.1 [40].

Table 7.1: The components of the Arizona Test Dust.

CAS No.	**Components**	**Quantity [%]**
14808-60-7	Silica (fine dust)	69-77
1344-28-1	Aluminium oxide	8-14
1305-78-8	Calcium oxide (mineral)	2.5-5.5
12136-45-7	Potassium oxide (mineral)	2-5
1313-59-3	Sodium oxide (mineral)	1-4
1309-37-1	Iron(III) oxide (hematite)	4-7
1309-48-4	Magnesium oxide	1-2
13463-67-7	Titanium dioxide	0-1

To induce limestone-like characteristics of the dirt, *Kaolin* was included in the mixtures. *Kaolin* also acts as a binder, due to its properties of becoming a slurry when mixed with water. The *Kaolin* material, hydrated aluminum silicate, is also referred to as Bole white that is washed. The density of the *Kaolin* is $0,5\ g/cm^3$. The formula of the material is presented in Table 7.2 [41].

Table 7.2: The molecular formula of Kaolin.

CAS No.	**Formula**
1332-58-7	$Al_2SiO_7\,2H_2O$

The materials were mixed in water to achieve different concentrations in order to simulate different dirt scenarios. The recipes of the different test scenarios can be seen in Table 7.3.

Table 7.3: Recipes for dirt mixes used during different tests.

Material	Hardened Test	Wet Test	Mud Splash Test	Dust Test
Water [g]	100	100	100	0
Kaolin [g]	40	40	80	20
Arizona Dust [g]	20	20	80	80

As for cleaning liquids, both water and washer fluid were used. The water is regular tap water. The washer fluid is Volvo's ready-made washer fluid mixed to withstand temperatures of -20°. The two fluids were tested individually and were not mixed during any test.

7.1.4 Test Limitations

The test site conditions set limitations on the comparability of the results in relation to the actual working conditions of the cleaning system. The environment in the lab can be considered stable regarding temperature and draft. Vibrations from the environment acting on the test rig are considered negligible. The conditions provided a good environment for comparative testing of different prototypes.

Due to limitations of the area available, there are deviations from the setup of a truck. The drawing of the hoses differed in lengths and radius to that of the truck. To facilitate quick changes in the test setup, the couplings and fittings chosen for the test setup differed from the couplings and fittings used on a truck regarding types, sizes and quantity. The air supply system installed in the facility performs differently to the air system of the truck. However, the compressed air supplied in the dirt laboratory has to travel in lengthy pipes.

The regulators provided to the test setup were fitted with analog dial indicators. This made exact readings of the pressures difficult. The regulators and dial indicators had no documented calibration leading to uncertainty regarding their accuracy. Moreover, accuracy is also affected by the reading of the values. The same regulators and indicators were used for all test, see Figure 7.3. The values relative to each other can, however, be considered accurate leading to good accuracy in a result relative to another.

Figure 7.3: The regulators used during the testing.

7.2 Leak Test

The first conducted test was a *Leak Test*. This was done to get an initial answer to how the material responded to the internal pressure. This meant observing if the interfaces kept a tight seal, ensuring reliable data from future tests because of the lack of losses due to leakage. The test was performed by plugging the cleaning heads' outlet holes, submerging the prototypes in water, pressurizing them from 1 to 5 bar and to watch for bubbles.

The *Leak Test* of the *Solid Prototype* showed minor leakage in a few outlets. The leakage appeared in outlets where the quality of the threads did not match the quality of the other threads. This was expected since the human error when threading the holes was known before the test started. The leakage was considered to be within the limit of acceptance since the leakage was relatively small in relation to the levels of pressure. The amount of leakage decreased with an increased amount of thread tape. A completely tight seal was not achieved for the used pressure range, however, the inlets kept a tight seal. When consulting personnel in A-hallen, the common conclusion was that the amount of leakage was not significant enough to impact the reliability of further testing. The performance of the *Solid Prototype* made the group confident in moving forward with further testing of the *Solid Prototype*.

The first *Leak Test* of the *Divided prototype*, showed significant leakage between the two parts. The screw joint without sealant or adhesive between the two parts did not create the required seal. In the second *Leak Test*, silicone supplied by Volvo was used to seal the two parts. The silicone was allowed to set the recommended time. Nonetheless, it still showed unacceptable leakage between the two parts affecting test data in future tests. In the third attempt, the parts were joined with *Loctite 4070* and left to cure for 48 hours. This test showed no leaks between the joined parts. The plugged outlets, fitted with thread tape on the plugs, held a tight seal up to 8 bar. At 8 bar, leakage was observed in the form of small and infrequent air bubbles. The conclusion was that the leak was not significant enough to impact the reliability of future test data. The result of the third test of the *Divided Prototype* made the group confident in moving forward with further testing of the *Divided Prototype*. In addition, insights in sealing PA 12 material that is SLS printed were collected.

7.3 Pressure Drop Test

The second test conducted was a *Pressure Drop Test*. This test was done to ensure that the geometry of the channels and the size of the inlet hoses were sufficient to supply the nozzles with the fluid required to successfully clean the LiDAR. This was needed since company representatives from the nozzle manufacturers uttered concerns whether the chosen design and hose dimensions would be able to provide enough fluid to all nozzles. The test was conducted by installing a tee coupling in the outlet holes of the cleaning head. The tee coupling was fitted with its assigned nozzle and a pressure gauge adapter, see Figure 7.4.

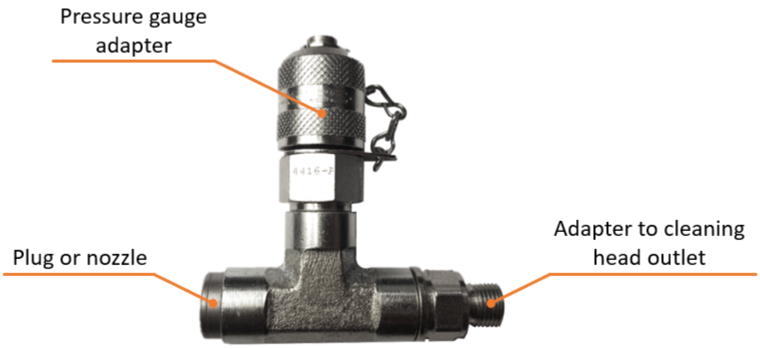


Figure 7.4: The tee coupling with seals, adapter, nozzle and pressure gauge adapter attached.

The pressure reading was first recorded at a manometer fitted to the regulators. The pressures were set with the valves located after the regulators, this reading was called closed pressure. When the valves were open and the fluids were flowing, the recorded pressure was called open pressure. The portable manometer attached to the pressure gauge adapter at the tee coupling was monitored when the flow was turned on. The test was repeated for all outlets individually by moving the portable manometer to each outlet position before pressurizing the system. The results can be seen in Table 7.4.

Table 7.4: Measured pressure at different positions for Solid Prototype.

Inlet Hose Size [mm]	**Inlet Pressure, Closed System [bar]**	**Inlet Pressure, Open System [bar]**	**Nozzle Pressure [bar]**					
			Pos. 1 Air	**Pos. 2 Air**	**Pos. 3 Air**	**Pos. 4 Air**	**Pos. 5 Air**	**Pos. 6 Air**
12	3	2,5	1,5	1,5	1,5	1,5	1,5	1,5
	5,5	4,75	3,1	3,1	3,1	3,1	3,1	3,1
	8	6,5	4,4	4,4	4,4	4,4	4,4	4,4
16	3	2,4	2	2	2	2	2	2
	5,5	4,6	3,8	3,8	3,8	3,8	3,8	3,8
	8	6,6	5,5	5,5	5,5	5,5	5,5	5,5
			Pos. 1 Water	**Pos. 2 Water**	**Pos. 3 Water**	**Pos. 4 Water**	**Pos. 5 Water**	
8	2	1,7	1,6	1,6	1,6	1,6	1,6	
	2,9	2,5	2,4	2,4	2,4	2,4	2,4	
	6	5,4	4,85	4,85	4,85	4,85	4,85	
12	2	1,7	1,9	1,9	1,9	1,9	1,9	
	2,9	2,5	2,7	2,7	2,7	2,7	2,7	
	6	5,4	5,55	5,55	5,55	5,55	5,55	

The results of the test indicated that a pressure drop did occur between the pressure registered for the closed system and the pressure at the nozzles with an open system. A pressure drop was registered for all hose dimensions. Potential reasons for this are described in Section 7.1.4. These pressure drops were regarded as acceptable because of its magnitude and that pressure losses occur in the current truck. The magnitude of these losses are of less importance since sufficient pressure was achieved and that the pressure drop can be counteracted by raising the pressure in the truck in an actual implementation.

Even with the pressure drop, the nozzle pressure recorded was regarded as sufficient in order for the nozzles to have potential to perform sufficient cleaning. A factor that strengthens this conclusion is that the additional manometers and fittings required to perform the test add resistance to the fluids path, increasing the potential pressure drop [42]. It was also found that all nozzles were provided the same pressure. This meant that the group could move forward assuming no discrepancy in cleaning performance between nozzle positions, removing the need to account for that in future testing.

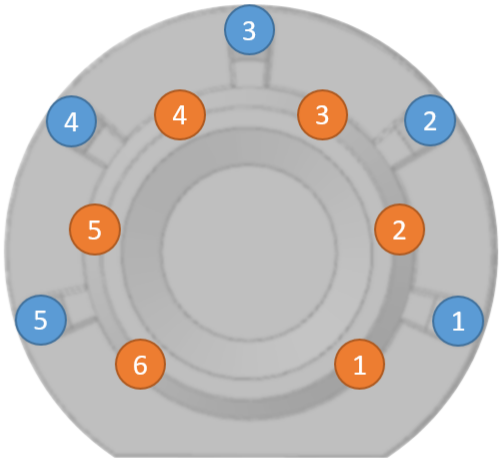


Figure 7.5: The Solid Prototype seen from below. The nozzle positions are numbered, orange represents the air nozzles and blue represents the water nozzles.

7.4 Volumetric Water Flow Rate Test

The third performed test was a *Volumetric Flow Rate Test*. This was done to ensure that the new design had a more efficient fluid release than the design currently implemented on the trucks. This test was important since the minimizing fluid consumption of solution was seen as one of the thesis's major goals, see Section 1.2.

To ensure a higher quality of the test data, the length of the hoses used in the test was setup to match the actual hoses. It makes the setup as comparable to the actual working conditions as possible. The tests were performed by turning on the system for a specified time and collecting the released fluid in a tray. The tray was weighed before and after the test on a scale with a tolerance of 20 grams. The weight of the fluid was translated to volume. To ensure better reliance of the test, the system was kept open for 40 seconds. This was done to make the results more comparable comparison easy and to minimize the effect of human lag in opening and closing the system on the exact time. The volumetric flow rate was calculated using Equation 3.2, see Section 3.4.1.

The measured average volumetric flow rate of the *Solid-* and *Divided Prototype* are presented in the Tables 7.5 and 7.6 respectively. With the addition of one added nozzle for the *Divided Prototype,* the flow rates increases with approximately 11 percent with a 8 mm hose, and 16 percent with a 12 mm hose.

Table 7.5: Measured average volumetric water flow rate for Solid Prototype. Open pressure $2,5$ bar with 8 & 12 mm hose.

Hose Dimension [mm]	**Test Duration [s]**	**Flow Rate [l/s]**	**Avg. Flow Rate [l/s]**
8	40	0,0555	
8	40	0,0555	0,0556
8	40	0,0560	
12	40	0,0585	
12	40	0,0605	0,0587
12	40	0,0600	

Table 7.6: Measured average volumetric water flow rate for Divided Prototype. Open pressure $2,5$ bar with 8 & 12 mm hose.

Hose Dimension [mm]	**Test Duration [s]**	**Flow Rate [l/s]**	**Avg. Flow Rate [l/s]**
8	40	0,0615	
8	40	0,0615	0,0617
8	40	0,0620	
12	40	0,0670	
12	40	0,0690	0,0680
12	40	0,0680	

A *volumetric Water Flow Rate Test* was performed of the current cleaning system to acquire reference data of the performance, see Table 7.7. With the current system, the flow rates are much higher when compared to the prototype. Furthermore, the flow rate increases close to 70 percent when the hose dimension is enlarged from 8 to 12 mm. An additional *Volumetric Flow Rate Test* was performed of the current cleaning system with lower pressures, see Table F.1 in Appendix F.

Table 7.7: Measured average volumetric water flow rate for current cleaning system. Open pressure $2,5$ bar with 8 & 12 mm hose.

Hose Dimension [mm]	**Test Duration [s]**	**Flow Rate [l/s]**	**Avg. Flow Rate [l/s]**
8	40	0,1230	
8	40	0,1235	0,1235
8	40	0,1240	
12	40	0,2075	
12	40	0,2045	0,2062
12	40	0,2065	

At higher pressures, the higher flow rate of the current cleaning system compared with the prototype is more evident. With a 12 mm hose and open pressure of 5 bar, the *Divided Prototype* consumes $0,0960$ l/s while the current cleaning system uses 0, 2995 l/s. The *Divided Prototype* uses less than a third of the current cleaning system's consumption with comparable setups.

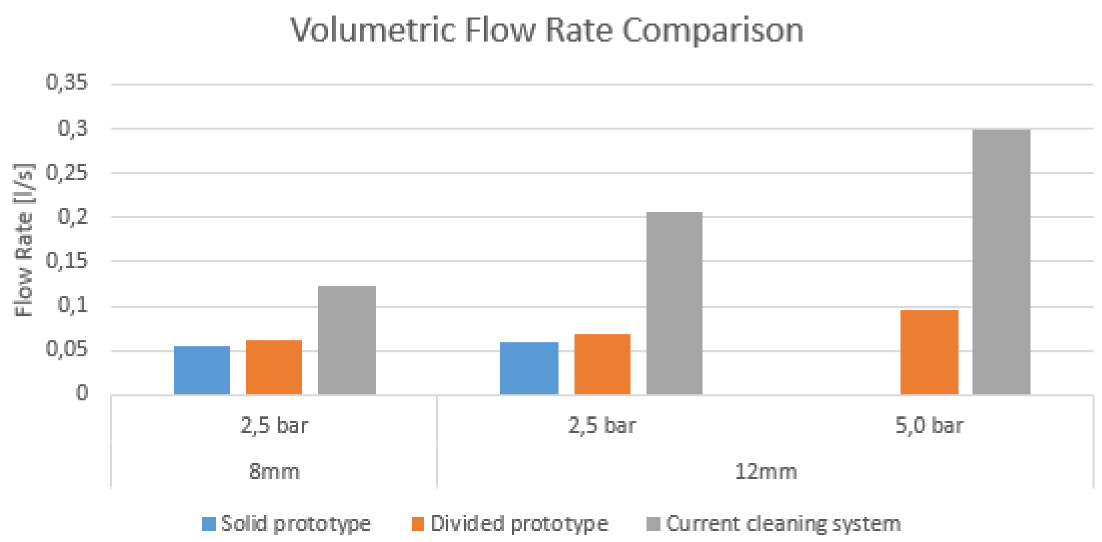


Figure 7.6: Volumetric water flow rate comparison between the variants of the prototype and the current cleaning system. Performed at different open pressures and with different hose dimensions.

Spraying System report that their B1/8HH spray nozzle has a volumetric flow rate of 0, 0123 l/s per nozzle at 3 bar pressure [39], see Figure 6.10. The average measured volumetric flow rate of the *Solid Prototype* with a hose dimension of 12 mm and a nozzle pressure of 2, 7 bar is 0, 0587 l/s. The *Solid Prototype* has five spray nozzles, resulting in a volumetric flow rate of 0, 0117 l/s per nozzle. Equation (3.3) presented in Section 3.4.1 is applied to calculate the theoretical flow rate at the same pressure as measured with the *Solid Prototype*, see Equation (7.1).

$$Q_m = Q_s \times n \times \sqrt{\frac{P_m}{P_s}} = 0,0123 \times 5 \times \sqrt{\frac{2,7}{3}} = 0,0585\ [l/s] \tag{7.1}$$

Q_m	=	The flow rate of *Solid Prototype* measured at 2,7 bar
Q_s	=	The flow rate per nozzle reported by the supplier at 3 bar
P_m	=	2,7 bar measured pressure
P_s	=	3 bar
n	=	Number of nozzles

The calculated volumetric flow rate, 0, 0585 l/s, of the nozzle at 2, 7 bar make it evident that the nozzles in the *Solid Prototype* is fully utilized at this pressure. The small difference that is observed is not significant enough to draw conclusions from as the margin of error from the testing method is possibly larger.

The *Pressure Drop Test* was not performed for concept *Divided Prototype*. However, with the measured the volumetric flow rate known, it is possible to determine the approximate pressure at the nozzles. The average measured volumetric flow rate of the *Divided Prototype* with a hose dimension of 12 mm and open pressure of $2,5$ bar is $0,0680$ l/s. The *Divided Prototype* has six spray nozzles, resulting in a volumetric flow rate of $0,0113$ l/s per nozzle. By using Equation (3.3) with Spraying System's values for the nozzle at 3 bar and solve for P_u, the pressure at the nozzles is calculated, see Equation (7.2).

$$P_u = P_s \times \left(\frac{Q_u}{Q_s \times n}\right)^2 = 3 \times \left(\frac{0,0680}{0,0123 \times 6}\right)^2 = 2,5332\ [bar] \tag{7.2}$$

Q_u	=	The flow rate of *Divided Prototype* measured at unknown pressure
Q_s	=	The flow rate per nozzle reported by the supplier at 3 bar
P_u	=	Unknown pressure
P_s	=	3 bar
n	=	Number of nozzles

7.5 Performance Test

The fourth test executed was a *Performance test.* The test was divided into three steps, *Air Test*, *Water Test* and a *Combination Test.* The reason for the test is to validate the design by evaluation of the cleaning performance. This involved validating that the distance to the optics cover and impact angle of the liquid onto the optic cover is correct, that the fluids coverage of the optics cover is sufficient to clean required field of view and that a successful cleaning sequence can be achieved within the time requirement. To lower the complexity of the testing and receive reliable data, air distribution and water distribution will be tested individually to eliminate the potential of the two fluids influencing each other. In the final *Performance Test*, the *Combination Test*, the full cleaning system will be tested. Parts of the *Combination Test* will also be performed on the current solution. From these tests, a comparison of the solutions and an evaluation of the new design can be made.

7.5.1 Placement of Cleaning Head

Before the *Performance Test* commenced, a test of the cleaning head placement was performed. This was done to validate that the coverage and angle of impact, see section 6.3, correlated to the 3D model and that the coverage and impact were sufficient to begin testing. The LiDAR was adjusted to its correct position in the horizontal plane and tested at four different heights. The height was altered in increments of 3 mm, ranging from -3 to $+6$ mm of the height in the original 3D model. The height of the cleaning head in relation to the LiDAR can be seen in Figure 6.12.

During testing, water and air were applied on the LiDAR. The coverage of the applied water was observed and recorded. When drying, it was observed and documented how the compressed air dried and removed the water. To further confirm coverage, the team did hands-on evaluation of the coverage by feeling the profiles impact area. The air phase was performed at $5, 5$ and 8 bar and air was applied for 5 and 10 seconds. The results of the test are presented in Table 7.8.

Table 7.8: Result of placement test.

Height [mm]	**Air**	**Water**
−3	Low impact of profile	Very good coverage
Original position	Good coverage	Good coverage
+3	Very good coverage	Good coverage
+6	High impact of profile	High impact of profile

It was concluded from testing that no significant improvement in drying could be seen between 5 and 10 seconds of drying cycles at 8 bar. It was also concluded that 8 bar dried the LiDAR more effectively than 5 bar. The +6 mm height was discarded as water accumulated on top of the LiDAR and that the shelf was not sufficiently dried. This was probably due to its high position. The −3 mm height was discarded due to insufficient drying of the optics cover, and mainly the top part of the optics cover. This was probably due to its low position. The +3 mm outperformed the original position on drying the optics cover while still performing sufficient drying of the shelf. The +3 mm also dried the vertical edge above the optics cover to a larger extent than the original height, while still not accumulating water on top of the LiDAR. Based on the results, the decision to use the +3 mm height was taken.

7.5.2 Air Test

From the *Pressure Drop Test*, see Section 7.3, it was concluded that inlet hoses of diameter 12 mm and 16 mm was sufficient to supply all nozzles with a homogeneous pressure. It was decided to perform an *Air Test* to investigate the drying capacity, regarding drying time and efficiency, with the respective hose dimensions. The objective was to acquire enough knowledge about the difference in drying capacity between hose dimensions to give recommendations on which hose dimension to be used during further testing. The *Solid Prototype* was used during testing.

The test was performed by first wetting the LiDAR with water and thereafter apply air at different pressure levels. The air was kept on until the surface appeared dry. The time was recorded manually along with a grade on how dry the surface actually became. The LiDAR was observed by a team member subjectively grading the level of dryness of the optics cover and shelf. The test was done two times for each pressure level and hose dimension. Grade 1 corresponds to very wet and grade 5 is completely dry. The results from the *Air Test* can be seen in Table 7.9.

Table 7.9: Results from the Air Test. The pressures given is closed system pressure.

Hose [mm]	Pressure [bar]	Time, 1st test [s]	Grade, 1st test	Time, 2nd test [s]	Grade, 2nd test	Time Avg. [s]	Grade Avg. [s]
12	3	9,2	3	6,7	3	7,95	3
12	5,5	4,1	3	4,8	3	4,45	3
12	8	2,3	4	3,1	3	2,7	3,5
16	3	7,9	3	6,4	2	7,15	2,5
16	5,5	3,1	3	4,4	3,5	3,75	3,25
16	8	3,1	4	3,4	4	3,25	4

It can be seen in Table 7.9 that an increase in pressure has a positive impact on the time needed to dry and the dryness grade achieved during the air sequence. From Table 7.4 it can be seen that the pressure levels tested equals nozzle pressures of $1,5$ - $5,5$ bar. It can also be observed that the positive aspects of increasing the pressure are not as significant at higher pressure levels. This holds true for both hose dimensions. It was concluded that the difference in time and grade between the two hose dimensions is not significant enough to rule out human error interfering in evaluating dryness and clocking the time. However, the differences in time and grade for the individual hose dimensions are significant enough that a pattern of improvement with higher pressures becomes obvious.

The results of the *Air Test* leads to the advancing of 12 mm hose and a higher pressure levels, such as of $5,5$ bar at the nozzle. With these selections, 4 seconds of applied air should sufficiently and consistently dry the wet optics cover and shelf. The flow rate of *Silvent 961* can be considered to increase linearly with pressure, see Figure 6.6 in Section 6.2. With linear interpolation, it is calculated that the flow rate at $5,5$ bar per air nozzle corresponds to $5,8$ l/s. The air consumption over 4 seconds with the seven air nozzles of the *Divded Prototype* corresponds to $162,4$ liter.

7.5.3 Water Test

After the isolated testing of the air performance in the *Air Test*, an isolated test of the water performance was performed. This test was named the *Water Test*. The test was done in order to investigate the effect water pressure has on the water's cleaning performance for future testing. The test was set up by first applying the dirt mix according to the recipe of *Hardened Test*, see Table 7.3 in Section 7.1.3. The mix was applied as uniform as possible on both the shelf and optics cover. The applied mix was thereafter carefully hardened by using a pneumatic gun to completely dry out the dirt mix, creating a hard and dry surface on the optics cover, see Figure 7.7. The dirt scenario was chosen since it was believed to be the toughest kind of dirt to clean out of the four scenarios to be tested. Hose dimension of 12 mm provides the cleaning head with more fluid per unit time and was therefore selected to initiate the investigate its potential cleaning ability. The 12 mm hose is chosen over the 8 mm hose because of its higher believed potential of *Action*, see section 3.3.2, *Mixing* and *Rinsing*, see section A.4 and A.5 in Appendix A. The test was carried out for both *Solid-* and *Divided Prototype*.

Figure 7.7: Hardened wet mix applied to the LiDAR.

The test was performed by applying water onto the surface at different pressures and measuring the time elapsed until a perceived clean optics cover and shelf was achieved. Between tests, the LiDAR and cleaning head was thoroughly cleaned and dried.

The closed pressures during test ranged between $2,9$ and $7,5$ bar. The perceived time elapsed until the LiDAR was clean was approximately 4 seconds at $4,5 - 7,5$ bar of closed inlet pressure. At a closed inlet pressure of $2,9$ bar, the time elapsed until the LiDAR was perceived clean was more than 7 seconds. This result, similar to the results obtained during the *Air Test*, indicates that a cleaning performance increases with increased pressure. However, the increase in performance is greater for increases at lower pressure levels. Increases in pressure at higher pressure levels yield smaller performance increases. It was also found that higher pressure of the water achieved better cleaning of the neglected area, see Figure 7.8, described further in Section 6.3.

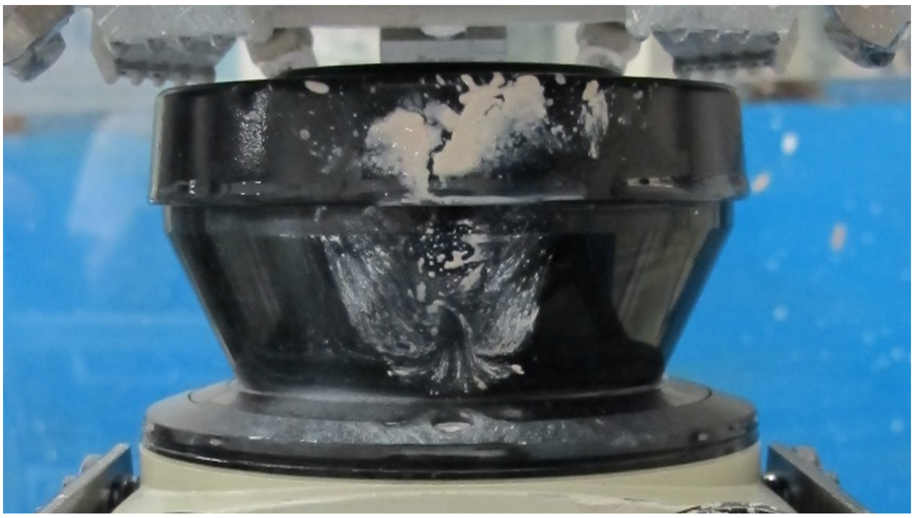


Figure 7.8: Neglected area of the LiDAR after applying water and air with Divided Prototype.

During testing, it was found that after the surface was perceived as clean and the water supply was shut off, dirt residue was sporadically left on the optics cover and shelf. This was not visible by inspection directly after the water was shut off, but became evident when the air nozzles dried the surface. One or both components in the dirt mix re-appeared on the surface, increasing its surface coverage with over the drying process and at spots left a thin film of dirt on the shelf and optics cover. The film only became evident after long drying sequences and high flow rates of air.

During testing, it was also observed that the dirt applied to the vertical edge above the optics cover became wet. The *Full Cone* spray from the water nozzles pushed the dirty water upwards while cleaning the optics cover. After applying water, the dirty water at the edge dripped down at the optics cover and the shelf, making the previously cleaned surfaces dirty, see Figure 7.9. This might have added to the problem of re-appearance of dirt after drying previously mentioned.

Figure 7.9: Re-appearance of dirt on the optics cover and shelf

7.5.4 Combination Test of Divided Prototype

In the *Combination Test*, four primary dirt scenarios were tested and evaluated when cleaning with the *Divided Prototype*. The learnings and selections of both *Air Test* and *Water Test* were utilized. Therefore, the cleaning fluid was applied at the closed pressure of $4,5$ bar. Cleaning fluid was used to replicate the liquid applied when cleaning in the project. The compressed air was applied at the closed pressure of 8 bar. During the testing, the cleaning sequence used to clean the LiDAR affected by the different dirt scenarios varied. The cleaning fluid was timed and applied until the optics cover and shelf were perceived clean. The compressed air was applied for a fixed time of 4 seconds with a pause of 2 seconds between the fluids. As previously done, the LiDAR and cleaning head was thoroughly cleaned and dried between tests. The test was set up by first applying the dirt mix according to the recipe of the different tests, see Table 7.3 in Section 7.1.3.

During the *Hardened Test*, see Figure 7.7, similar results to those in the *Water Test* were achieved. The optics cover and shelf appeared clean after 4 seconds of applied cleaning fluid. However, the hardened dirt of the vertical edge above the optics cover became wet as previously observed. Droplets of the wet dirt dripped down which led to re-appearance of dirt on the optics cover during the 4 seconds of drying.

The *Wet Test* uses the same dirt mixture as *Hardened Test*, although not dried prior to testing, see Figure 7.10. Despite this difference, the outcome was very comparable to the *Hardened Test* with approximately 4 seconds of cleaning liquid and observed re-appearance of dirt. The correlation between the two tests is the applied amount of the wet mixture being applied.

Figure 7.10: Wet mix applied to the LiDAR.

The *Mud Splash Test* simulates the scenario where the LiDAR is subjected to large splashes of mud, see Figure 7.11. The measured time needed to achieve a clean optics cover and shelf varied greatly during the *Mud Splash Test*. During testing, the time of applied cleaning liquid varied between 4 - 25 seconds to successfully clean. The measured times were inconsistent, partly due to deviations in applying the mixture. It was noticed that dirt from the mud splash appeared more difficult to remove when located at the edge of two water nozzles' coverage. Effects of insufficient rinsing and coverage are described in Section A.5 in Appendix A. The large quantity of dirt mixture and the fact that the mixture has a lower portion of water to the dry materials most likely affects the cleaning performance. The potential effects of soil levels are explained in Section A.2 in Appendix A.

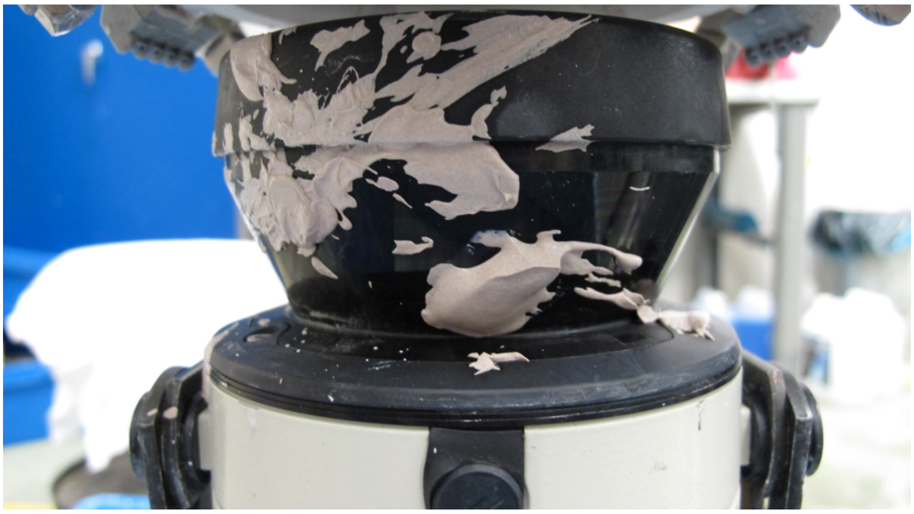


Figure 7.11: Mud Splash mix applied to the LiDAR.

In the *Dust Test*, a thin and uniform layer of the dry *Dust Test* mixture was applied to the LiDAR, see Figure 7.12. The cleaning fluid required to be sprayed for less than 2 seconds during all tests to remove the applied dust. The dust was also removed at the neglected rear facing part of the LiDAR. After drying for the fixed 4 seconds, the optics cover and shelf were completely dry with no dirt remaining.

Figure 7.12: Dust mix applied to the LiDAR.

During the *Combination Test* of the *Divided Prototype* it was evident that cleaning fluid remained in the hose and channels of the prototype after the cleaning fluid supply was shut off. Occasionally leading to dripping from the spray nozzles. The drops were absorbed by the air stream, re-introducing the cleaning fluid to the dried surfaces.

7.5.5 Combination Test of Current Cleaning System

In the *Combination Test*, the current cleaning system was tested in order to benchmark *Divided Prototype* to an existing product. The same four dirt scenarios were tested with the same closed pressure of 4, 5 and 8 for the cleaning liquid and air respectively with hose dimensions of 12 mm. However, the pressures at the orifices distributing the fluids are unknown. In contrast to the testing of *Divided Prototype*, an *Air Test* has not been performed. Therefore, the time of applied air to dry is not fixed, rather it is applied until the surfaces are perceived dry. The dirt mixtures were applied with the same methods as previously. Figure 7.13 shows the *Hardened Test* mixture applied to the LiDAR. None of the tests were performed more than two times.

Figure 7.13: Hardened wet mix applied to the LiDAR prior to testing the current cleaning system.

The cleaning fluid had to be applied for 9, 5 seconds in the *Hardened Test* to achieve surfaces that appeared clean from the hardened dirt mixture. Thereafter, it took about 30 seconds of applied air to dry. The surface of the shelf was occasionally still moist after being dried. In addition, there are dirt residuals in the angle between the optics cover and shelf as well as on the shelf and optics cover themselves. The very top edge of the optics cover together with sporadic dots of dirt remained after the cleaning sequence. It could also be observed that the vertical edge above the optics cover was neither subjected to wetting or drying. The rear-facing part of the LiDAR was cleaned to the same degree managed by *Divided Prototype*.

In the *Wet Test*, 4, 5 seconds of cleaning liquid and 30 seconds of air was needed to clean and dry the LiDAR. In this test, only a few dots of dirt mixture remained on the shelf. On the other hand, substantial re-appearance of dirt developed on the optics cover where the air stream is directed, see Figure 7.14.

Figure 7.14: Re-appearance of dirt developed on the optics cover where the air stream is directed from the current cleaning system.

The cleaning fluid required to be sprayed for 8 seconds during the *Mud Splash test* to remove the applied dirt. The air needed 35 seconds to achieve an optics cover and shelf that were perceived dry. It could be observed during the test that there was no dirt remaining on the optics cover and shelf. During the *Dust Test*, the dirt was removed within $1,5$ seconds of applied cleaning fluid. The air was however applied for the much longer time of 32 seconds. It resulted in an optic cover and shelf that were both clean and dry. During all tests of the current cleaning system, the first 8 seconds of applied air did not dry the surfaces. Throughout this period, the cleaning liquid remaining in the system was applied and foaming occurred on the surface, see Figure 7.15. The occurrence was expected due to an earlier investigation into the current cleaning system and the fact that it shares channels for distribution of cleaning fluid and air. It should also be mentioned that the larger flows of cleaning liquids obstructed the view making it difficult to perceive when the LiDAR was clean.

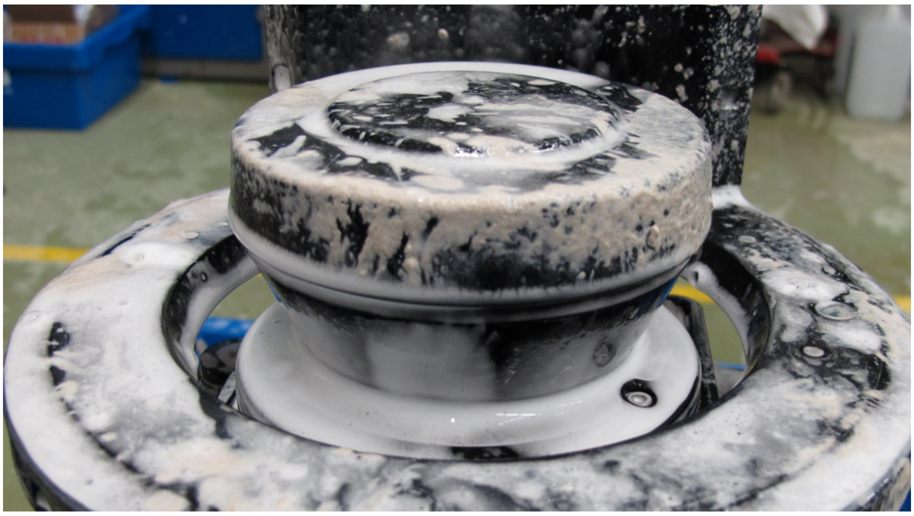


Figure 7.15: The foam on the LiDAR after applying air for 8 seconds with the current cleaning system.

7.5.6 Comparison and Evaluation

It is important that the times presented are regarded as the cleaning sequence needed to achieve the results presented in the *Combination Test*. The level of cleanliness and dryness of the optics cover and shelf vary. In addition, there are other areas such as the vertical edge above the optics cover that has an impact on the outcome. The current cleaning system was not tested at different pressures in contrast to *Divided Prototype*. These factors should be remembered when comparing *Divided Prototype* to the current cleaning system. In Figures 7.16 to 7.19, the time of the cleaning sequence are compared.

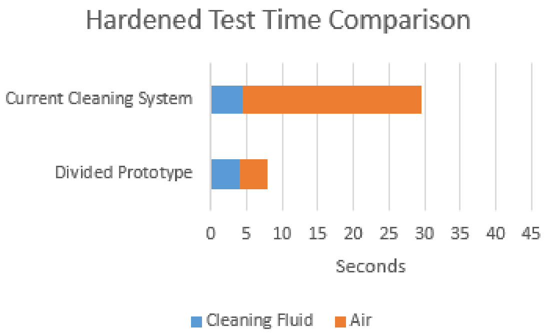


Figure 7.16: Hardened Test time comparison.

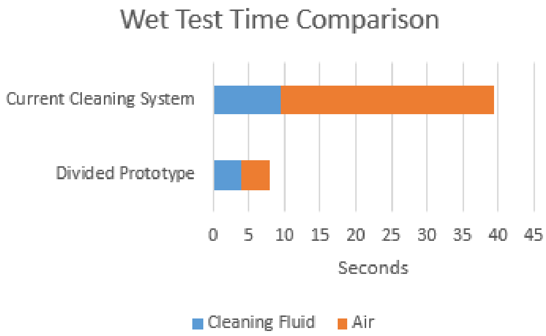


Figure 7.17: Wet Test time comparison.

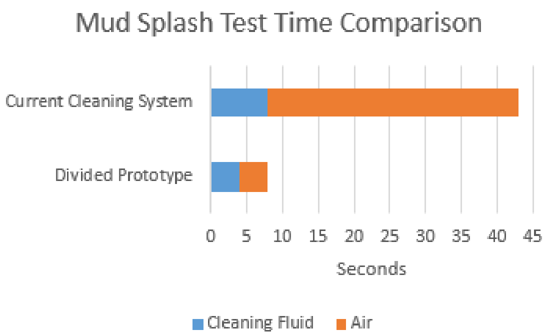


Figure 7.18: Mud Splash Test time comparison.

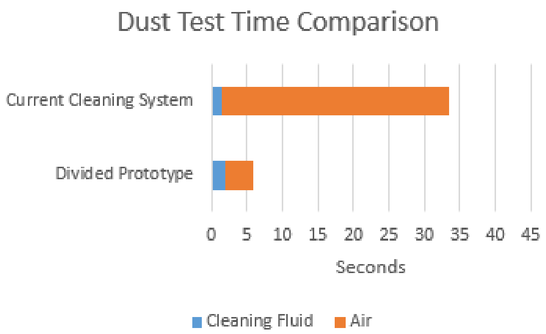


Figure 7.19: Dust Test time comparison.

To acquire the volumetric water flow rate of the current cleaning system at a closed pressure of 4, 5 bar, an additional *Volumetric Flow Rate Test* was carried out. The test showed that the current cleaning system uses 0, 2400 l/s. The volumetric flow rate of the *Divided Prototype* is not measured at a closed pressure of 4, 5 bar. However, it can be assumed to approximately corresponding to a pressure of 4 bar at the nozzles when reviewing the pressure drops observed in Section 7.3. If the *Divided Prototype's* volumetric flow rate with 5 bar at the nozzles is assumed to be the same as the open pressure. The volumetric flow rate at 4 bar at the nozzles can be calculated, see Equation (7.3).

$$Q_t = Q_m \times \sqrt{\frac{P_t}{P_m}} = 0,0960 \times \sqrt{\frac{4}{5}} = 0,0859\ [l/s] \quad (7.3)$$

Q_t = The flow rate of *Divided Prototype* in *Combination Test* at 4 bar
Q_m = The flow rate of *Divided Prototype* measured at 5 bar
P_t = 4 bar estimated test pressure
P_m = 5 bar

With the volumetric flow rates at 4, 5 bar closed pressure known for both the current cleaning system and *Divided Prototype*, the consumption can be compared. The *Divided Prototype* consumes less than 36 percent per second in comparison to the current cleaning system. The required time to apply cleaning fluid differs between the solutions and vary depending on the scenario. Therefore, the cleaning fluid consumption of the different dirt scenarios are compared, see Figure 7.20. The total amount of liquid consumed by the *Divided Prototype* is between 0, 1718 and 0, 3436 liter during the cleaning of the different dirt scenarios. This can be compared to the current cleaning system's consumption of 0, 3600 to 2, 2800 liter.

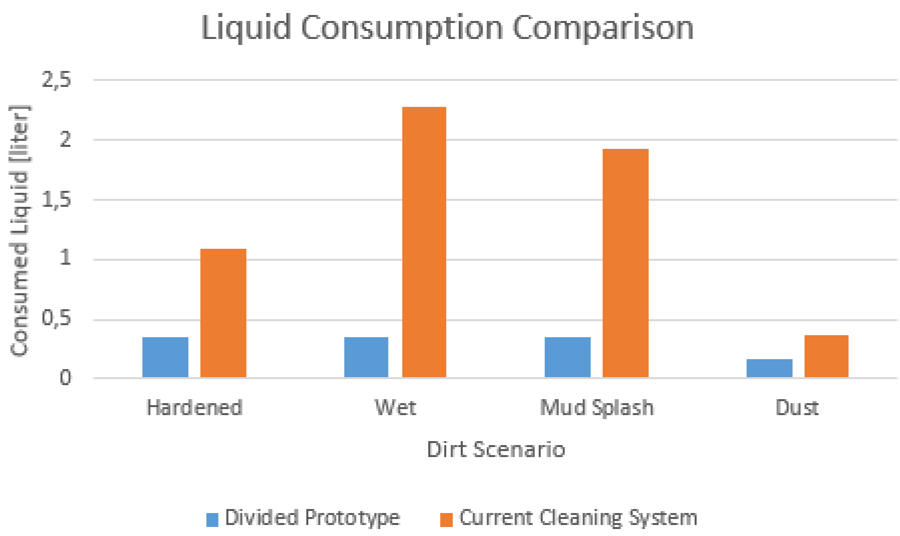


Figure 7.20: Comparison of the liquid consumption of the different dirt scenarios.

The performance of the *Divided Prototype* was evaluated to the *Specification of Requirements*. Especially fulfillment of the most important criteria presented in Table 4.1 in Section 4.4.3. The liquid consumption for *Divided Prototype* of between 0, 1718 and 0, 3436 liter is well below the requirement criteria 1.4 of less than 0, 75 liter per cleaning sequence. However, the ambitious desire to consume less than 0, 25 liter stated in criteria 1.5 was not achieved in most dirt scenarios. The maximum time the cleaning fluid is applied is 4 seconds, followed by 4 seconds of applied air. The total time of the cleaning sequence is thereby less than the desire, criteria 1.13, of a cleaning sequence shorter than 10 seconds.

Furthermore, it is possible to evaluate if the *Divided Prototype* fulfilled the requirements and desires related to achieving clean surfaces, criteria 1.18 and 1.19. The results during the testing are promising in this regard. The large quantities of dirt applied on the optics cover and shelf was removed. In addition, the surfaces were effectively dried. However, the re-appearance of dirt is problematic and had a large impact on the cleanliness in the *Combination Test*. The desire to not needing an additional cleaning sequence, criteria 1.15, is also difficult to evaluate as it is related to the same problem.

7.5.7 Additional Tests

Besides the more thorough tests performed, additional tests were performed to increase knowledge and find potential opportunities for improved performance and usability. However, these additional tests should be regarded as preliminary studies with indications of what might occur.

Cleaning with heated water, at approximately 50°C, with the *Divided Prototype* was tested. The test was performed as the temperature is one of the four cleaning parameters that greatly affect the process, see Section 3.3.3. With increased temperature of the applied water, a tendency to measurably faster cleaning of the LiDAR was observed.

A preventive test of continuously blowing air at 8 bar closed pressure was carried out to study the potential of trying to avoid the need for cleaning. Firstly, with the air turned on, the mix of *Dust Test* was attempted to be applied to the LiDAR. The air curtain created by the flat blow pattern manages to deflect close to all the dust. Secondly, water was sprayed to investigate if the blowing air would prevent the liquid from striking the LiDAR. It was observed that the water droplets were partly absorbed into the air stream. As the air stream of the air nozzles is directed at the optics cover and shelf, these surfaces became moist before being dried as the water spray was not continuous. Lastly, the mix of *Wet Test* was applied with the same conditions. However, the blowing air's barrier effect to the *Wet Test* mix when applying was not perceivable and the mix struck the LiDAR.

Instead of applying the liquid followed by air, different cleaning sequences were also tested. In one of these tests, the liquid and air were applied in short bursts repeatedly. It was also tested to apply the liquid and air simultaneously which changed the coverage and increased the *Action*. It was not observed that the diverging cleaning sequences reduced the consumption or the total time of the cleaning sequence. Nonetheless, areas that persisted to remain dirty were at times cleaned faster.

8

Design Recommendations

This chapter aims to provide the reader with recommendations on the future design of a LiDAR cleaning system. The design recommendations originate from analyses of the design phases and testing phase. The recommendations mainly regard the hardware and geometry of the cleaning system, but recommendations on other design aspects will be made. The recommendations are summarized in a design proposal in the end of the chapter.

8.1 Design Aspects

It is evident from the results of the *Pressure Drop Test*, see Table 7.4, that increasing the hose dimension reduces the pressure drop in the system. It can also be seen in Table 7.9 that increased pressure leads to a faster successful cleaning sequence. Figure 7.6 shows that increased pressure levels leads to higher flow rates. Based on these results the recommendation for future designs of the cleaning system is that the choice of hose dimension and pressure level should be decided based on the application. However, with the investigated design, higher air pressure is recommended when it is required to dry a surface quickly and yet efficiently. Increased liquid pressure was also observed to be beneficial. The benefits were limited when increasing the pressure beyond certain levels with the investigated design.

In Figure 7.6 the volumetric flow rate of the different solutions are shown. The improved flow rate of the new designs is primarily due to the use of nozzles, more specifically fluid specific nozzles. The time needed to apply water to get the LiDAR clean, see Figure 7.16 to 7.19, are predominantly shorter for the new designs. Together with the improved flow rate, this leads to the conclusion that a design with fluid specific nozzles are beneficial regarding its resource efficiency.

A design with separate channels for the fluids is considered beneficial. It was seen during testing that residual cleaning liquid remains in the hose and channel of the current cleaning system. The residual liquid is dispensed in the early parts of the air sequence, prolonging the time needed to clean. Residual cleaning liquid has the risk of dripping from the nozzles in a design with separate channels, but the design shows a greater potential of overcoming the problem. In both designs, it is beneficial to locate the valves as close to the cleaning head as possible.

The Figures 6.16, 6.17 and Figure G.1 in Appendix G show the elimination of stress concentrations due to the rectangular shape of the channels. Based on the result from stress simulations and theory of losses, see Section 3.4.2, it is recommended that circular channels are introduced. It is also recommended to avoid sharp bends and corners in future designs.

A design with independent mounting surfaces for air nozzles and water nozzles are considered beneficial. This design aspect allows for independent adjustment of the direction of the fluids, such as angle and distance to the surface to be cleaned. In addition, the design feature allows for adaptions in order to function on various sizes and shapes of LiDARs. To illustrate the adaptability, Figure 8.1 shows a cylindrical LiDAR. The nozzles are positioned at distances and angles corresponding to the designed cleaning head. Moreover, the compactness of the solution remains as it is related to the size of the LiDAR. The combination of adaptions and possibility to select nozzles with specific spray patterns enables optimization of cleaning coverage and performance.

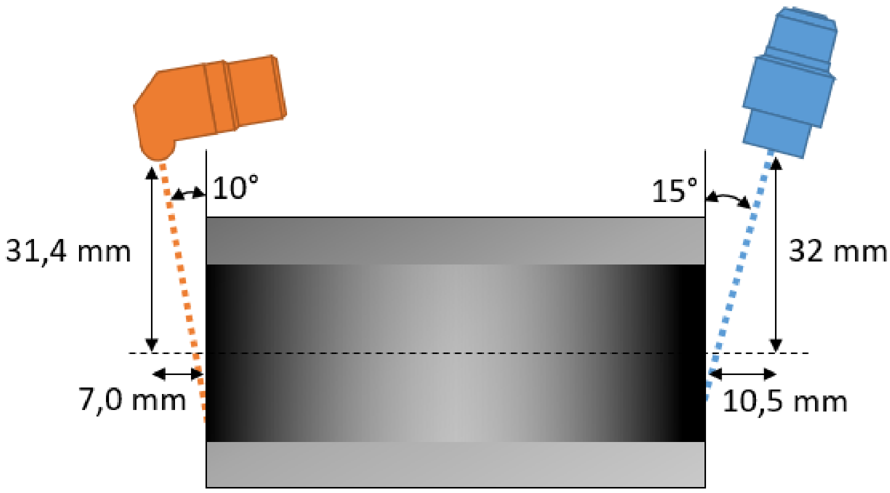


Figure 8.1: The placement of the nozzles on a LiDAR with cylindrical shape. The air and water nozzle is illustrated in orange and blue respectively.

8.2 Final Design Proposal

Based on the findings in the design and testing phase, the thesis workers created an updated conceptual design named *The Squid*, see Figure 8.2. The updates performed are in accordance with the recommendations previously presented in this chapter.

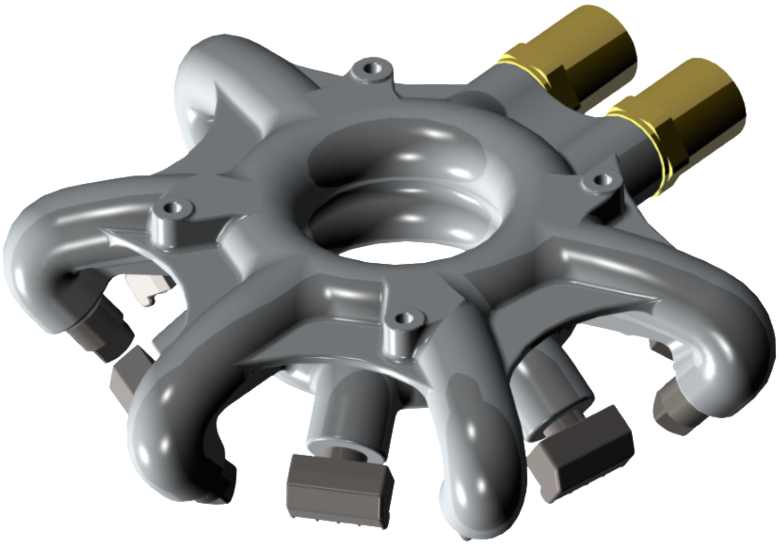


Figure 8.2: The Squid with mounted nozzles and couplings, seen from above.

The design of *The Squid* is adjusted to be manufactured through 3D printing. The design uses 50 percent less material then the tested prototypes, drastically reducing the weight of the cleaning head. This is done while still being structurally sound with maximum stress levels staying well below the stress limit of the material, see Figure G.2 and Figure G.3 in Appendix G. In *The Squid's* design, the fluid inlets are moved to the back of the cleaning head. It reduces the bend between the inlet hose and the internal channels reducing minor losses in the cleaning head. It also increases the compactness by placing hoses and couplings at the back, creating a slimmer appearance of the entire cleaning system.

The Squid concept has been designed with independent mounting surfaces for air and water nozzles, attached to individual arms with spacing in between, see Figure 8.3. This feature allows for easy access to the nozzles, leading to easier assembly and replacement of potentially malfunctioning nozzles. The number of nozzles, their coverage and angles are kept the same as previous prototypes due to positive results from the testing. However, *The Squid* allows for designs with an increased number of nozzles as well as fewer.

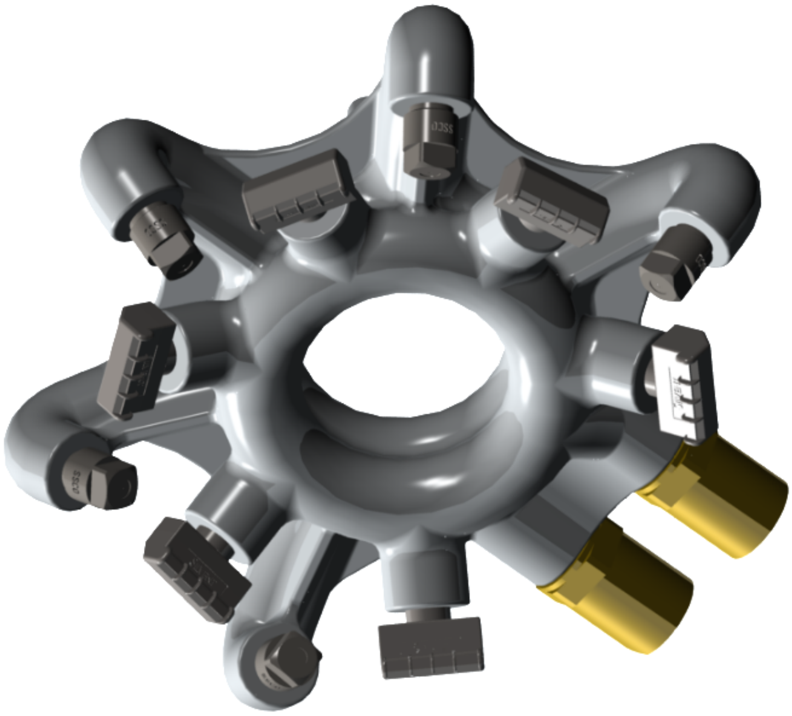


Figure 8.3: The Squid with mounted nozzles and couplings, seen from below.

9
Discussion

This chapter aims to provide the reader with the thesis workers' considerations regarding aspects of the performed work and its result. This is done in order to improve the overall understanding of the thesis work and its result. The chapter begins with a discussion regarding aspects influencing the workflow of the project. A discussion regarding the design follows. This is followed by a discussion regarding the testing and result of the design. A discussion regarding the relevance follows and the chapter is concluded with a discussion regarding potential ethical, economical and societal aspects of relevance for the thesis.

9.1 Remarks on Workflow

The workflow originally intended to be utilized in the thesis, see Section 2.1, had its foundation in theory frequently used in university courses taken by the thesis workers. During the thesis, a few tasks that were planned to be performed concurrently needed the result of other tasks. It caused parts of the workflow to occur in more of a waterfall structure. In order to utilize the time, the thesis workers were forced to approach other tasks without sufficient information. This was partly based on the thesis workers' inexperience with routines at Volvo. In addition, the knowledge of production lead times and skill in quickly accessing the correct contacts for information gathering were lacking. By planning and starting tasks with little knowledge, even though common in many professional situations, in combination with the short time frame of the thesis might have led to flexibility being lost in some processes. However, the results and knowledge obtained in the thesis are perceived to be of good quality and of potential value for Volvo. Therefore the negative effects on the thesis caused by the adjusted workflow can be seen as having little effect on the final result. The adaptation in the workflow was also successful from the perspective that the thesis work was finished within the set time frame.

9.2 Remarks on Design

Due to the novelty of the task to clean LiDARs, few requirements existed for the product set by Volvo or others. This lack of requirements, and overall in-depth knowledge of the problems became most evident through discussions with Volvo employees involved in the project. On several occasions, the thesis workers were given contradicting statements regarding problems, the reasons for the problems and which resources existed to fix the problems. For this reason, acquiring knowledge about how to best clean the LiDAR and the LiDAR cleaning system was of equal importance when designing the functional prototypes. The development of the cleaning system was application specific to the site. It enabled multiple requirements to be collected through existing data of operations and performed tests. The thesis workers were instructed that other aspects, such as LiDAR brand and model, would potentially be changed in the future leading to the need for a flexible cleaning system. This is considered to have been achieved, but with the risk that the proposed design is not optimal for the current LiDAR used. The developed cleaning system showed good potential during testing, but the complex shape of the LiDAR led to difficulties in cleaning all surfaces of the LiDAR. The complex shape of the LiDAR was also apparent when testing the current solution. For this reason, it is believed that a change to a LiDAR with less complicated shape would be beneficial, enabling more case-specific optimization.

To simplify purchasing and design a viable product, a desire from Volvo was that standard parts and systems currently used by Volvo were utilized to the largest extent possible. This reduced the design space of the product. However, it also reduced lead times in sourcing and acquiring material throughout the thesis work.

9.3 Remarks on Testing and Results

The novelty of the task of cleaning sensors means that no standardized method exists for testing. This led to the thesis workers having to design entirely new test methods. For this reason, uncertainties exist regarding the test results and the methods used. The potential sources for these uncertainties are the rig, the dirt scenarios tested, the dirt mixtures, its application method and the overall execution of the test. The tests were also performed on a LiDAR not connected to a computer. Therefore, the LiDAR was unable to use its dirt level detecting system to report to the thesis workers how clean was clean enough. This made the performance to be measured by comparative observations. For these reasons, the tests were designed to provide comparative results rather than results enabling optimization of the cleaning system. The results are seen as having good quality and should be used as guidelines in future works, but not as absolute learnings. Due to the apparent future potential of autonomous vehicles, the thesis workers identify these learnings to be of high interest for Volvo in order to design a standardized method for testing sensor cleaning in the future. This would allow for fewer uncertainties in the results and ease comparison between tests executed on different occasions.

Another aspect of high interest in Volvo's future work with sensor cleaning would be to introduce fluid simulations in earlier phases of the cleaning system design. Fluid simulations could be used to in a more cost-effective manner test a large number of configurations. It would also allow testing of the cleaning system on other LiDARs and optimize fluid flow and coverage before manufacturing.

A potentially large opportunity when optimizing the cleaning system is to vary the cleaning sequence depending on the conditions. This is an aspect not extensively tested within this thesis work. Instead, the testing used cleaning sequences that had the potential to provide comparative results, with less effort into optimizing the individual sequences. Therefore, some of the dirt scenarios tested are deliberately hard to clean and might simulate more difficult scenarios than is present at the site. Simulations and tests of future interest could be different lengths of the applied fluids as well as applying, for instance, the cleaning fluid twice in a cleaning sequence. In addition, short preventive bursts of air during driving to dry moisture or acts as a barrier to prevent build up and hardening of dirt could be tested.

9.4 Relevance of the Thesis

As mentioned in Section 4.1, a patent search was performed by the thesis workers before starting the concept generation. At that time, no relevant patents were found being limiting to the thesis and very few patents regarding sensor cleaning systems were found overall within the search. Towards the end of the thesis work, a new patent search was made to renew the thesis workers knowledge about the status of the field of interest. During the second search, it was evident that a considerable amount of patents were publicized during the months of the thesis work. The patents mainly regard control systems for sensor cleaning systems on vehicles and not the hardware as is the case in this thesis. In that regard, the new patents are not limiting to the product developed in this thesis but proves the relevance of this thesis as it shows the effort and resources put into R&D within the field of sensor cleaning.

9.5 Ethical, Economical and Societal Aspects

At the start of the thesis work, the ethical aspects of executing the thesis work were considered. For the execution of the project, no ethical implications were found that motivated the thesis workers to refrain from executing the thesis. It was due to the small risk for negative effects on mental and physical health and invasion of privacy for the people involved during the thesis work's different phases.

As for the result of this thesis, the LiDAR cleaning system, ethical considerations about potential implications are relevant. The result enables automation of the vehicle fleet which has the potential to improve logistics and transportation in a variety of areas. From a health perspective, functional autonomous vehicles will reduce monotonous driving tasks for human drivers. It will also reduce prolonged human presence in potentially harmful environments, such as in a mine.

One ethical implication is that functional autonomous vehicles reduce the need for human drivers. However, the decision to not implement autonomous vehicles might lower or even eliminate future competitiveness of the entire mining operation resulting in economical and societal effects. Autonomous vehicles have the potential to increase operational efficiency by optimizing routes, driving patterns and up-time of the trucks. These aspects have the potential of increased resource efficiency, with local and global societal benefits. Increased resource efficiency can also in a longer perspective be a vital argument from an economical and ethical point of view, due to the global trend of penalizing resource consumption associated with climate change. Increasing operational efficiency also helps to maintain job opportunities for the company and its suppliers. Keeping a competitive edge on the market can be seen as having positive ethical and economical implications due to the benefits for all stakeholders within the project.

This leads the thesis workers to conclude that the effects of the potential result of the thesis motivate execution of the thesis.

10
Conclusion

The purpose of this thesis was to develop a functioning and reliable LiDAR cleaning system, while being of value for Volvo's future work on sensor cleaning. The developed concept has throughout the thesis showed promising results on cleaning and overall functionality. The results and analysis of the thesis have also answered questions regarding relevant technologies of interest in the field of sensor cleaning providing knowledge valuable for Volvo in future development projects.

The most important performance enhancement with respect to the current LiDAR cleaning system, the improved fluid consumption, is achieved using fluid specific nozzles. Utilization of fluid specific nozzles requires separate channels for the fluids. When benchmarking, it was evident that designs with the cleaning head placed above the LiDAR yield positive effects. The current LiDAR requires the optics cover and the shelf with IR-sensors being cleaned, which is advantageously done from above to achieve the necessary coverage. It is also beneficial when designing since the cleaning head does not compete for space around the LiDAR.

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 PA 12. The advantage of 3D printing was found to be the improved design possibilities and scalability of complicated geometries while allowing for drastic reductions in weight.

In the thesis work, the developed prototype was benchmarked against the currently implemented cleaning system on Volvo's autonomous trucks. For this reason, the test data is identified as useful and applicable to the current project. However, the comparative nature of the tests limited investigation of the full potential and drawbacks of the prototype. This in turn limits the possibility to accurately compare it to upcoming solutions utilizing different technologies. It was identified that there are several aspects and parameters influencing the cleaning system's performance, which together with knowledge gaps due to the novelty of sensor cleaning led to exploratory and somewhat unreliable testing during the thesis. Therefore, Volvo is recommended to develop a standardized testing method for sensor cleaning systems to ensure reliable and accurate data.

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A
Factors Affecting Cleaning

The following paragraphs explain relevant factors that affects the need for cleaning performance and sets requirements on the level of cleaning parameters, accounted for in section 3.3.

A.1 Surface

Two aspects of the surface affects the cleaning process. The chemistry of the surface has an effect on how strong the bond between the soil and the surface will be. Surface finish also affects the result of the cleaning process. A rough finish leads to a larger contact surface between the soil and the surface to be cleaned. Very rough surfaces can also lead to issues in transporting the soil away from the cleaned area, depositing residue in cracks [13].

A.2 Soil Level

Soil levels on the surface affects the result of the cleaning process. Excessive levels of soil on the surface can potentially leave the current set of parameters inadequate to loosen and remove the accumulated soil. This can happen if the ratio between cleaning solution and soil is wrong and/or if the force acting on the soiled surface is insufficient to remove the soil [13].

A.3 Soil Condition

The condition of the soil affects the requirements on the cleaning system since wet or ”fresh” soil do not require the same amount of cleaning agent to be loosened up. This has the effect that smaller amounts of force are needed to remove the soil. This is dependent on the soil present, where some types of soil can be easier to remove in a dryer state due to lesser weight of the soil to be removed. The soil condition has implications on the timing of the cleaning process where the time between the area being soiled and the time for cleaning can have big effects on the result, where a short interval are generally beneficial [13].

A.4 Mixing

Mixing is the process where unsoiled cleaning solution comes in contact with unaffected soil. Good mixing of the cleaning solution enables even cleaning of the treated surface, and reduces the risk of local depositions of soil due to insufficient application of cleaning solution. It is important for the cleaning process that the entire surface to be cleaned is subjected to fresh cleaning solution for the solution utilize its full potential. Imperfections in mixing has the possibility to be compensated with an increase in time concentration [13].

A.5 Rinsing

Rinsing with water occurs after the application of the cleaning solution. Sufficient rinsing is important to remove potential residue from the surface, demanding good surface coverage to be effective. Rinsing can reduce the need for high temperatures if the solution is easily risible with water. Increasing the risibility of the cleaning solution allows for lowering of the demands on the time needed for rinsing. During rinsing it is important to remove potential residues of the cleaning solution. Rinsing of the cleaned surface is preferably done shortly after the process, in order to prevent loosened soil to dry back on the cleaned surface [13].

B
Company Guidelines

To allow for cross-functional understanding at Volvo, a set of definitions are put in place regarding parameters of importance during the product development process. The parameters are defined and explained in the *Global Transportation Application* (GTA). These parameters works as primary input data in development and verification for everything from components to complete vehicles. Parameters are grouped together by their function such as *operating environment*, *transport mission* and *vehicle utilization* etc.. This allows Volvo to categorize vehicles and streamline the process of providing the right vehicle for the intended use and application.

B.1 Transport Mission

The transport mission relates to the job that is to be performed by the truck, such as hauling cargo or transporting passengers. That in turn determines the vehicle size and type, gross vehicle/combination weight and body. The transport mission is established so that Volvo can provide the right truck to the customer, allowing for optimal utilization of the load capacity and maximizing the income generated by the vehicle. This must be done within the applicable vehicle regulations.

B.2 Vehicle Utilization

Vehicle utilization reflects the cycles, such as how often it stops to load or unload goods or passengers during its operation. The GTA defines four basic operating cycles, stop and go, local, regional and long distance. The differentiating factor is the mean distance between delivery or pickup of goods. This can in turn provide Volvo with probable characteristics of the application, such as average speed. To assess the vehicle utilization GTA also grades the number of speed changes, the need for maneuvering and the yearly usage.

B.3 Operating Environment

To ensure the correct vehicle specification is created Volvo investigates the condition the vehicle works in based on certain parameters, named the operating environment. Road condition regards the road surface and its condition and are graded smooth, rough, very rough and cross country. Topography is assessed by the maximum gradient of the route as well as if a certain percentage of the route exceeds a certain gradient. The classes of topography are flat, predominantly flat, hilly and very hilly. The operating environment also considers altitude, ambient temperature and curve density.

C

Specification of Requirements

Table C.1: Specification of Requirements.

Specification of Requirements						
Development of a LiDAR Cleaning System for Autonomous Trucks						
	Criteria	Target value	R/D	Weight	Evaluation/Verification	Justification
Function	A sensor cleaning system					
1	Performance					
1.1	Ambient upper service temperature	Up to +40°C	R		Material data	Operational design domain ATU40
1.2	Ambient lower service temperature	Down to -25°C	R		Material data	Operational design domain ATL25
1.3	Ambient temperatur when not in service	−25°C to +40°C	R		Material data	Operational design domain
1.4	Liquid usage per successful cleaning sequence	< 0,75 L	R		Testing	Limited liquid tank
1.5	Liquid usage per successful cleaning sequence	< 0,25 L	D	5	Testing	Limited liquid tank
1.6	Keep air usage above lower threshold of existing air tank	> 8,5 bar	R		Testing	Safety, air compressor performance
1.7	Not decrease LiDAR horizontal FoV	270°	R		3D modelling	Keep functionality of LiDAR
1.8	Should not obstruct the emitted laser pulse	0% obstruction of emitted beam	R		3D modelling	Keep functionality of LiDAR
1.9	Should not obstruct the receiving laser pulse	≥ 30mm vertical gap	R		3D modelling	Keep functionality of LiDAR
1.10	Prevent frost cracking	Remove liquids in system	D	2	Testing	Decrease downtime
1.11	Manage vehicle speed	50 km/h	D	3	Testing/Simulation	Function when driving
1.12	Length of cleaning sequence	< 20 sec	R		Testing	Decrease downtime
1.13	Length of cleaning sequence	< 10 sec	D	5	Testing	Decrease downtime
1.14	Full functionality of system after cold-start	Within 5 minutes	R		Testing	Decrease downtime
1.15	No need for additional cleaning sequence	95% of the time	D	4	Testing	Limited liquid tank
1.16	Number of cleaning sequences possible at the same time	≥ 1 sequence	R		Testing/Simulation	Decrease downtime
1.17	Manage vibrations	4g	R		Testing/Simulation	Increased service life of product
1.18	Should clean the entire FoV	270°	R		Testing	Keep functionality of LiDAR
1.19	Should clean all IR-sensors	7 IR-sensors	R		Testing	Keep functionality of LiDAR
1.20	No glare reaching the LiDAR sensor	0% glare	R		Testing	Keep functionality of LiDAR
1.21	Minimize potential for removed residues to obstruct view once removed		D	3	Testing/Simulation	Limited liquid tank
1.22	Dimensions including helmet W×H×D	160×200×160 mm	D	3	3D modelling	Flexibility in positioning
2	Quality					
2.1	Product service life	> 5 years	R		Testing	Decrease downtime
2.2	Robust against change of LiDAR		D	4	3D modelling	Cost efficiency
2.3	Should not attatch to LiDAR		D	2	3D modelling	Not interfere with alignment of LiDAR
2.4	Should not damage optical window of the LiDAR	No abrasive action	R		Testing	Keep functionality of LiDAR
2.5	Change of wearing parts	Possible without destructive disassembly	D	4	Testing	Cost efficiency
3	Material					
3.1	UV-resistance during product lifespan	Should not impact functionallity	R		Material data	Increased service life of product
3.2	Corrosion resistance during product lifespan	Should not impact functionallity	R		Testing/Material data	Increased service life of product
3.3	Resistant to chemicals during product lifespan	Should not impact functionallity	R		Material data	Increased service life of product
4	Production and installation					
4.1	Assembly time		D	5	Testing	Decrease labour costs
4.2	Installation time		D	5	Testing	Decrease labour costs
5	Compability to truck system					
5.1	Compatible with current air system	Minor changes are acceptable	R		3D modelling	Cost efficiency
5.2	Compatible with current liquid system	Minor changes are acceptable	R		3D modelling	Cost efficiency
5.3	Work together with the new design of helmet	Minor changes are acceptable	R		3D modelling	Cost efficiency
6	Service and access					
6.1	Service interval	> 6 months/service	R		Testing	Cost efficiency, decrease downtime
6.2	Minor maintenance	> 1 week/maintenance	D	3	Testing	Cost efficiency, decrease downtime
6.3	Easy to clean	Easy access	R		Ergonomic simulation	Cost efficiency, decrease downtime

D

Function Means Tree

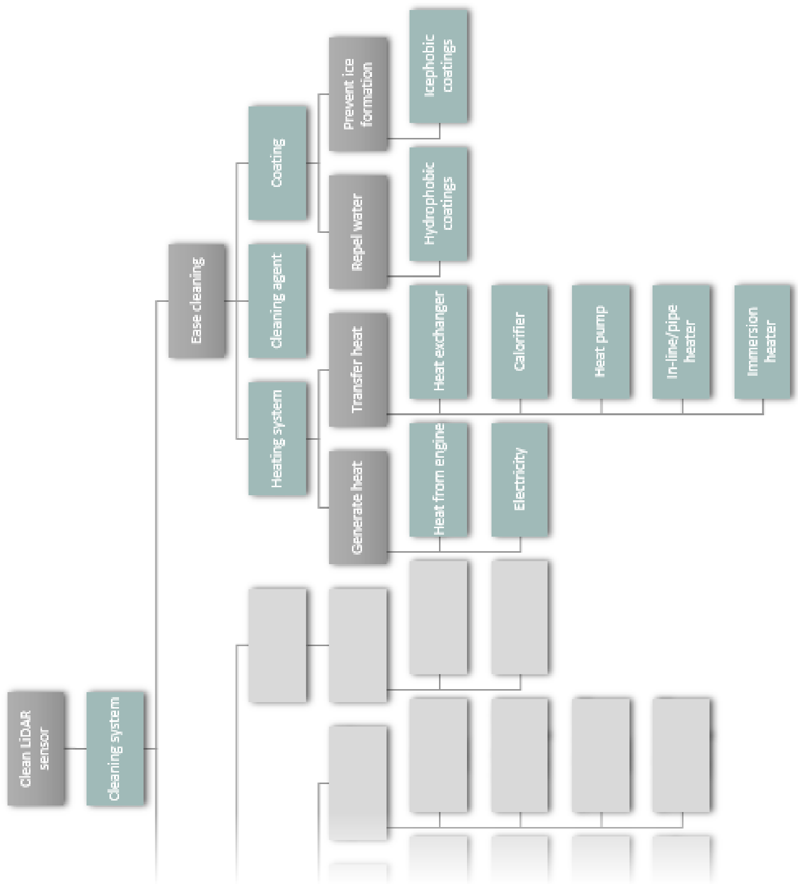

Figure D.1: Function Means Tree showing the branching from the sub-function Ease cleaning. Showing the right side of the complete Function Means Tree.

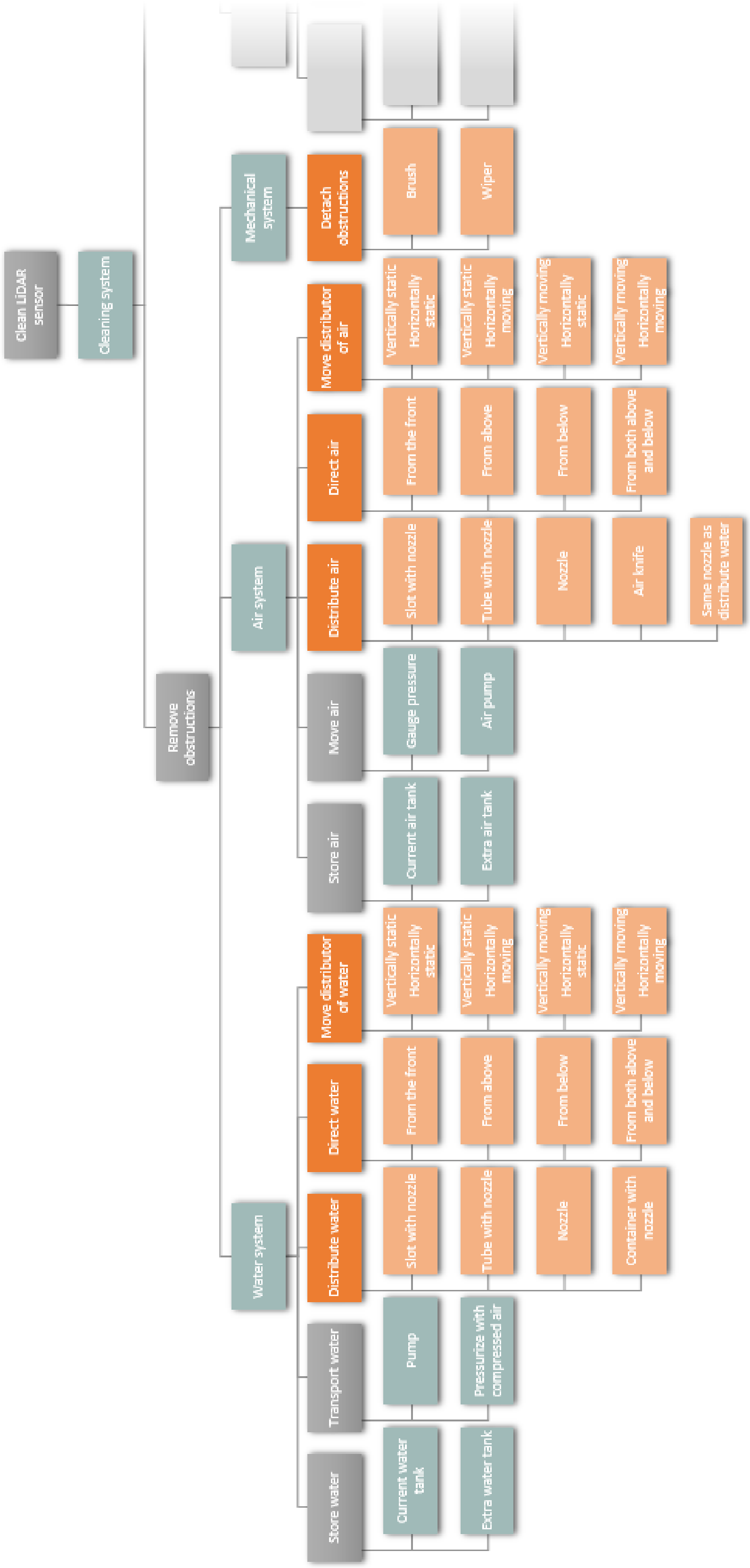

Figure D.2: Function Means Tree showing the branching from the sub-function Remove obstructions. Showing the left side of the complete Function Means Tree.

E

Morphological Matrix

Morphological Matrix						
Development of a LiDAR Cleaning System for Autonomous Trucks						
		Sub solutions				
Sub functions		1	2	3	4	5
Distribute water	A	Slot with nozzle	Tube with nozzle	Hose with nozzle	Container with nozzle	
Direct water	B	From the front	From above	From below	From both above and below	
Move distributor of water	C	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Distribute air	D	Slot with nozzle	Tube with nozzle	Hose with nozzle	Air knife	Same as distibute water
Direct air	E	From the front	From above	From below	From both above and below	
Move distributor of water	F	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Detach obstructions	G	Brush	Wiper			

Figure E.1: Morphological Matrix.

Top Plate						
		Sub solutions				
Sub functions		1	2	3	4	5
Distribute water	A	Slot with nozzle	Tube with nozzle	**Hose with nozzle**	Container with nozzle	
Direct water	B	From the front	**From above**	From below	From both above and below	
Move distributor of water	C	**Vertically static Horizontally static**	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Distribute air	D	Slot with nozzle	Tube with nozzle	Hose with nozzle	Air knife	**Same as distibute water**
Direct air	E	From the front	**From above**	From below	From both above and below	
Move distributor of water	F	**Vertically static Horizontally static**	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Detach obstructions	G	Brush	Wiper			

Figure E.2: Morphological Matrix of concept Top Plate.

Fixed Ring		Sub solutions				
Sub functions		1	2	3	4	5
Distribute water	A	Slot with nozzle	Tube with nozzle	Hose with nozzle	Container with nozzle	
Direct water	B	From the front	From above	From below	From both above and below	
Move distributor of water	C	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Distribute air	D	Slot with nozzle	Tube with nozzle	Hose with nozzle	Air knife	Same as distibute water
Direct air	E	From the front	From above	From below	From both above and below	
Move distributor of water	F	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Detach obstructions	G	Brush	Wiper			

Figure E.3: Morphological Matrix of concept Fixed Ring Below.

Solid Ring Above		Sub solutions				
Sub functions		1	2	3	4	5
Distribute water	A	Slot with nozzle	Tube with nozzle	Hose with nozzle	Container with nozzle	
Direct water	B	From the front	From above	From below	From both above and below	
Move distributor of water	C	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Distribute air	D	Slot with nozzle	Tube with nozzle	Hose with nozzle	Air knife	Same as distibute water
Direct air	E	From the front	From above	From below	From both above and below	
Move distributor of water	F	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Detach obstructions	G	Brush	Wiper			

Figure E.4: Morphological Matrix of concept Solid Ring Above.

Spinning Ring		Sub solutions				
Sub functions		1	2	3	4	5
Distribute water	A	Slot with nozzle	Tube with nozzle	Hose with nozzle	Container with nozzle	
Direct water	B	From the front	From above	From below	From both above and below	
Move distributor of water	C	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Distribute air	D	Slot with nozzle	Tube with nozzle	Hose with nozzle	Air knife	Same as distibute water
Direct air	E	From the front	From above	From below	From both above and below	
Move distributor of water	F	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Detach obstructions	G	Brush	Wiper			

Figure E.5: Morphological Matrix of concept Spinning Ring.

Spinner		Sub solutions				
Sub functions		1	2	3	4	5
Distribute water	A	Slot with nozzle	Tube with nozzle	Hose with nozzle	Container with nozzle	
Direct water	B	From the front	From above	From below	From both above and below	
Move distributor of water	C	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Distribute air	D	Slot with nozzle	Tube with nozzle	Hose with nozzle	Air knife	Same as distibute water
Direct air	E	From the front	From above	From below	From both above and below	
Move distributor of water	F	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Detach obstructions	G	Brush	Wiper			

Figure E.6: Morphological Matrix of concept Spinner.

Wiper		Sub solutions				
Sub functions		1	2	3	4	5
Distribute water	A	Slot with nozzle	Tube with nozzle	Hose with nozzle	Container with nozzle	
Direct water	B	From the front	From above	From below	From both above and below	
Move distributor of water	C	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Distribute air	D	Slot with nozzle	Tube with nozzle	Hose with nozzle	Air knife	Same as distibute water
Direct air	E	From the front	From above	From below	From both above and below	
Move distributor of water	F	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Detach obstructions	G	Brush	Wiper			

Figure E.7: Morphological Matrix of concept Wiper.

The Clash		Sub solutions				
Sub functions		1	2	3	4	5
Distribute water	A	Slot with nozzle	Tube with nozzle	Hose with nozzle	Container with nozzle	
Direct water	B	From the front	From above	From below	From both above and below	
Move distributer of water	C	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Distribute air	D	Slot with nozzle	Tube with nozzle	Hose with nozzle	Air knife	Same as distibute water
Direct air	E	From the front	From above	From below	From both above and below	
Move distributer of water	F	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Detach obstructions	G	Brush	Wiper			

Figure E.8: Morphological Matrix of concept The Clash.

Top Plate Block		Sub solutions				
Sub functions		1	2	3	4	5
Distribute water	A	Slot with nozzle	Tube with nozzle	Hose with nozzle	Container with nozzle	
Direct water	B	From the front	From above	From below	From both above and below	
Move distributor of water	C	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Distribute air	D	Slot with nozzle	Tube with nozzle	Hose with nozzle	Air knife	Same as distibute water
Direct air	E	From the front	From above	From below	From both above and below	
Move distributor of water	F	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Detach obstructions	G	Brush	Wiper			

Figure E.9: Morphological Matrix of concept Top Plate Block.

Top Block		Sub solutions				
Sub functions		1	2	3	4	5
Distribute water	A	Slot with nozzle	Tube with nozzle	Hose with nozzle	Container with nozzle	
Direct water	B	From the front	From above	From below	From both above and below	
Move distributor of water	C	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Distribute air	D	Slot with nozzle	Tube with nozzle	Hose with nozzle	Air knife	Same as distibute water
Direct air	E	From the front	From above	From below	From both above and below	
Move distributor of water	F	Vertically static Horizontally static	Vertically static Horizontally moving	Vertically moving Horizontally static	Vertically moving Horizontally moving	
Detach obstructions	G	Brush	Wiper			

Figure E.10: Morphological Matrix of concept Top Block.

F

Testing and Evaluation

Hose Dimension [mm]	**Test Duration** [s]	**Flow Rate** [l/s]	**Avg. Flow Rate** [l/s]
8	40	0,1060	0,1078
8	40	0,1085	
8	40	0,1090	
12	40	0,1410	0,1457
12	40	0,1485	
12	40	0,1475	

Table F.1: Measured average volumetric water flow rate of current cleaning system. Open pressure of $1,95$ bar with 8 mm hose and $1,4$ bar with 12 mm hose.

G

Stuctural Analysis of Design Proposal

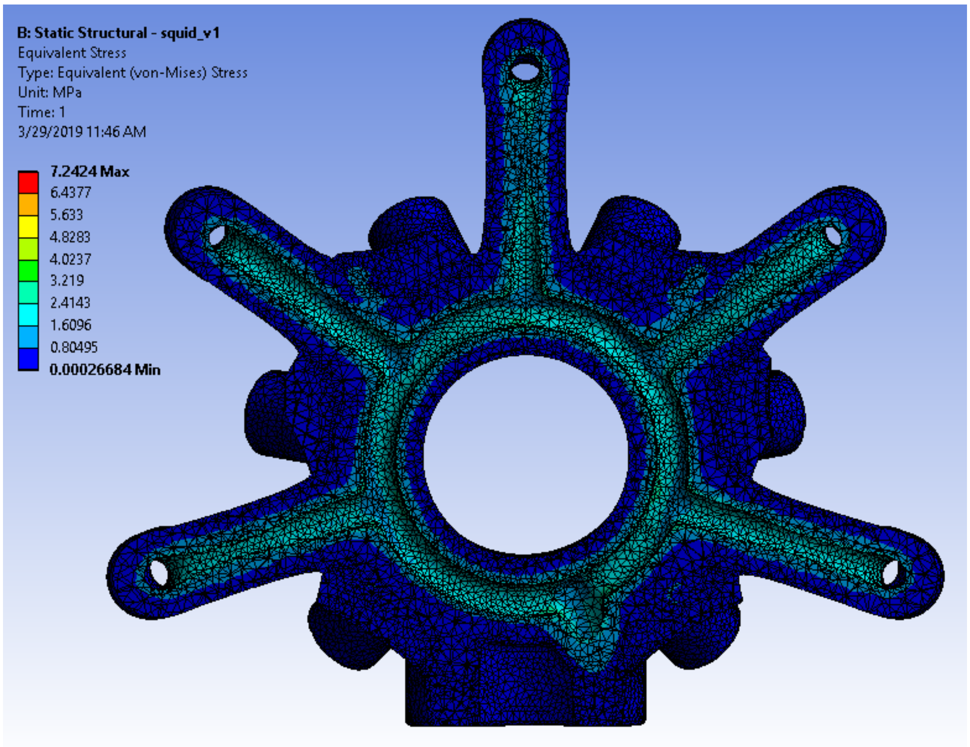

Figure G.1: Cross section of The Squid design showing the stress in the channels due to 10 bar internal pressure.

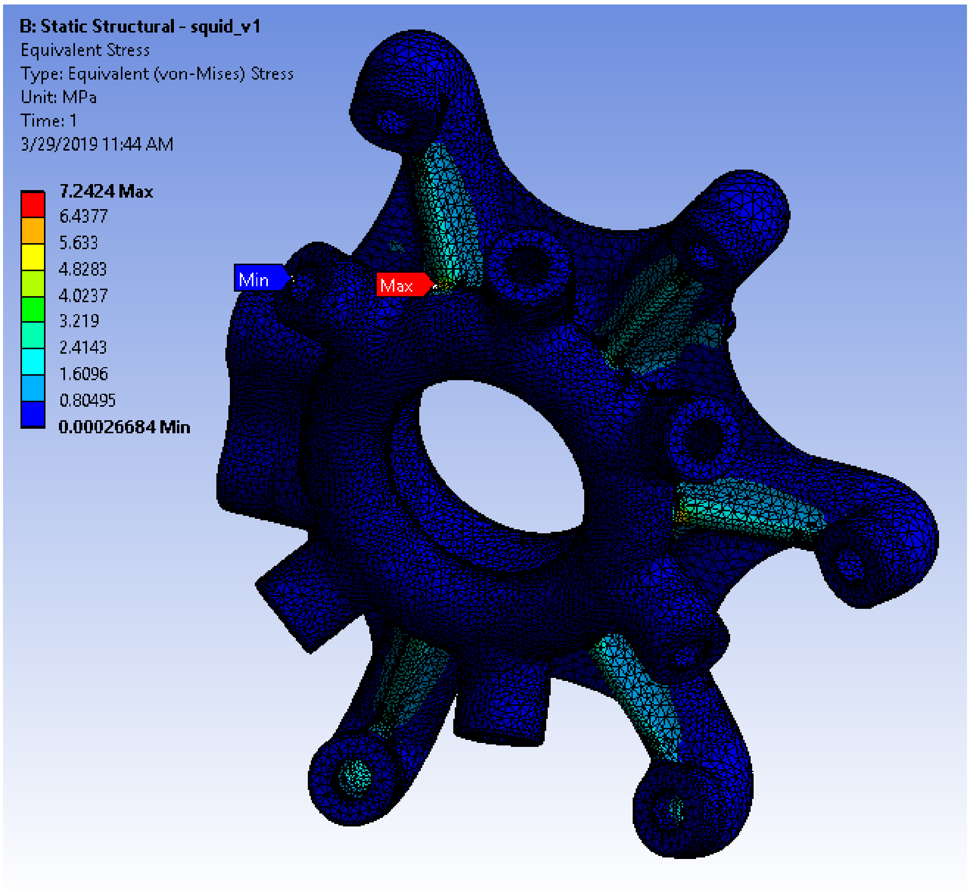

Figure G.2: The Squid design seen from below showing equivalent stress due to 10 bar internal pressure.

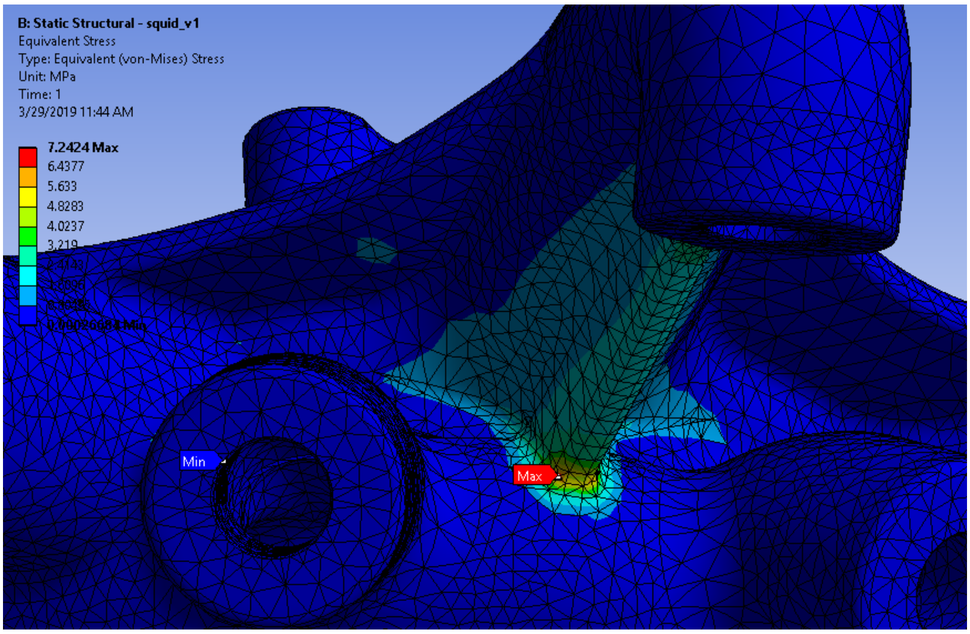

Figure G.3: The Squid design seen from below showing position of maximum equivalent stress due to 10 bar internal pressure.