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Housing prototype for autonomous driving sensor

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October 7, 2020

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Abstract

This work was carried out at Bosch's facilities at Braga. To meet the projected global growth of the autonomous vehicles, Bosch proposed to define a small and low-cost LiDAR (Light Detection and Ranging) sensor to be used in autonomous driving.

The automotive LiDAR sensor uses light to measure the distance of an object, pedestrians, street lighting poles, roads, being a critical component on autonomous vehicles. However, the automotive industry has some regulations that cover every device installed on a vehicle regarding the standard for electronics, mechanical, software and optics that regulates the environmental conditions experienced during manufacture, shipping, handling, storage, vehicle assembly and maintenance. On the market already exists some LiDARs however, currently those do not fulfill all the automotive standards.

For the Bosch LiDAR sensor, the requirements, specifications and components definition are defined mainly concerning the optical and electronic sub-systems. The housing chassis will be the mechanical support for these sub-systems, which will be developed in this project.

The main focus of this prototype development was the physical support for the Data handling and Advanced processing subsystems (electronic subsystem), which includes the PCB stack and the laser source. During the evolution of the designed parts, the automotive standards, as well as the requirements of the sensor, were pursued whenever possible, however, it was not a mandatory goal for this proof of concept. The designed parts for the prototype were specified regarding their function, material, geometry and manufacturing process. The designed parts, due to manufacturability limitations, had to be tweaked to accommodate said limitations.

As the electronic components will generate heat and the temperature of the components should increase but must be below their maximum operating temperature, otherwise, it will cause failures on the system. In this way, some thermal management solutions applied to the system include the usage of thermal bridges, thermal paste, extended surfaces and fans. It was decided to insulate thermally the electronic system (which generates heat) from the optics system (do not generate heat), by using low thermally conductive materials.

Experimental work was performed to monitor the temperature monitoring of the laser source and the FPGA (Field-Programmable Gate Array) component. Numerical simulations allowed to understand that the maximum operating temperature of the system was 70°C, that the fans only decrease the global system average temperature inside the housing approximately 1.28% whereas the forced convection due to rotation decreases the temperatures of the heat sources by nearly 50%.

Resumo

Este trabalho foi realizado nas instalações da Bosch em Braga. Para responder ao rápido crescimento global previsto para os veículos autónomos, a Bosch propôs a definição de um pequeno sensor LiDAR de baixo custo para ser utilizado na condução autónoma.

O sensor LiDAR utiliza luz para medir a distância de um objeto, peões, postes de iluminação pública, estradas, sendo um componente importante a utilizar em veículos autónomos. No entanto, a indústria automóvel tem algumas regulamentações que abrangem todos os dispositivos instalados num veículo no que diz respeito à norma relativa à eletrónica, mecânica, software e ótica que regula as condições ambientais experienciadas durante o fabrico, expedição, manuseamento, armazenamento, montagem e manutenção do veículo. No mercado já existem alguns sensores LiDAR, contudo, não cumprem algumas normas automóveis.

Para o sensor LiDAR Bosch, os requisitos, especificações e definição dos componentes são maioritariamente definidos os subsistemas óticos e eletrónicos. O chassis exterior será o suporte mecânico para estes subsistemas.

O foco principal deste trabalho foi o desenvolvimento de um protótipo físico para dar suporte ao subsistema *Data handling and Advanced processing* (parte eletrónica), que inclui a pilha de PCBs e a fonte laser. Durante a evolução das peças projetadas, as normas automóveis, bem como os requisitos do sensor, foram tidos em conta sempre que possível, contudo, não eram o objetivo para este protótipo. As peças desenvolvidas foram descritas quanto à sua função, material, geometria e processo de fabrico. Por questões de limitação dos processos de fabrico, algumas das peças desenhadas tiveram de ser ajustadas.

Os componentes eletrónicos irão gerar calor contudo, a temperatura destes componentes deverá ser inferior à sua temperatura máxima de funcionamento, caso contrário, irão ocorrer falhas no sistema. Desta forma, foram utilizados mecanismos de gestão térmica no sistema como: a utilização de pontes térmicas, pasta térmica, alhetas e ventoinhas. Decidiu-se isolar termicamente o sistema eletrónico (que gera calor) do sistema ótico (não gera calor), utilizando materiais de baixa condutibilidade térmica.

O trabalho experimental foi baseado na monitorização da temperatura da fonte laser e da FPGA. A simulação numérica permitiu definir que a temperatura máxima de funcionamento do sistema são 70°C, que as ventoinhas apenas permitem uma diminuição da temperatura média do ar dentro do sistema de 1,28%, enquanto que a convecção forçada devido à rotação permite uma diminuição da temperatura das fontes de calor de aproximadamente 50%.

Acknowledgements

Quero agradecer aos professores da FEUP, em particular ao orientador da tese, Professor Abílio, pela partilha de conhecimentos e ainda co-orientado, Professor Marco, e a todos aqueles que de certa forma se cruzaram no meu caminho durante o meu percurso académico.

Ao João Santos, orientador na Bosch pelo conhecimento, tempo dedicado, ajuda constante e ainda ao Eng. Alexandre Correia que foi fulcral na concretização desta dissertação e que sempre se prontificou a ajudar no que fosse necessário.

Ainda na Bosch, um agradecimento muito especial ao André Santos por toda a paciência. À Mónica, Bruno, João Nunes, e ainda a todos os elementos do ENG42 pelo momentos incríveis, boa disposição com os quais convivi diariamente, que desde o primeiro dia me fizeram sentir bem-vinda na equipa.

À parceira do estágio, Patrícia, pela motivação, entreaajuda e amizade que se desenvolveu ao longo deste percurso na empresa.

Um agradecimento aos meus amigos e confidentes: Varela, Paulo, Carolina, Leninha que sempre me motivaram e ajudaram a superar todas as minhas crises existenciais e a todos os elementos da barraquinha assim como ao Hugo, Boto e Bia que serão sempre lembrados com imensa nostalgia por todos os momentos incríveis.

Ao Diogo, por estar sempre ao meu lado, principalmente neste semestre tão atípico.

À minha família, pais Margarida e Mário e aos meus irmãos Mário e Carlinhos e ainda a todos os meus primos, tios e avós que durante estes 5 anos me apoiaram e motivaram nunca fechando portas a novos desafios.

Contents

1	Introduction	1
1.1	Context	1
1.2	Overview of the company	1
1.3	Motivation and goals	1
1.4	Thesis content	2
2	State of art	5
2.1	Autonomous driving	5
2.1.1	Autonomous driving levels	5
2.1.2	Sensors for autonomous driving	8
2.2	LiDAR sensor	10
2.2.1	LiDAR operating principle	11
2.2.2	LiDAR main components	12
2.2.3	ISO automotive requirements	13
2.2.4	LiDAR benchmark	15
3	System requirements and specifications	19
3.1	Optical system	19
3.2	Electronic components	20
3.2.1	Laser	20
3.3	Housing chassis requirements	21
4	Prototype development	25
4.1	Housing layout	25
4.2	Design, material, process, and geometry	28
4.2.1	Main exterior Chassis	29
4.2.2	PCB holder	30
4.2.3	Optics parts	33
5	Thermal management	39
5.1	Effects of temperature in LiDAR system	39
5.1.1	Thermal defocus	40
5.2	Thermal management solutions	41
5.2.1	Extended surfaces	42
5.2.2	Thermal bridges	49
5.2.3	Insulation materials	49
5.2.4	Fans	49
5.3	Components temperature monitoring	51

5.3.1	TE0820-03 Board	51
5.3.2	Laser Source	52
5.4	Numerical simulation	54
5.4.1	Heat sources	56
5.4.2	Initial temperature variation	58
5.4.3	Heat transfer mechanisms	61
5.4.4	Fans performance	63
5.4.5	Rotational effects	63
6	Functional prototype	67
6.1	Parts manufacturing	67
6.2	Assembly sequence	71
6.2.1	Fans assembly	72
6.2.2	PCBs assembly	72
6.2.3	Bottom holder assembly	73
6.2.4	Laser assembly	74
6.2.5	Main chassis assembly	74
6.2.6	Laser spacer assembly	74
6.2.7	Optics parts assembly	75
6.2.8	Top holder assembly	76
6.2.9	Final assembly	77
6.3	System industrialization	78
7	Conclusions and future works	79
7.1	Conclusions	79
7.2	Future work	80
	References	83
A	Technical Drawings	87
B	Data sheets	97
C	Materials	101

List of Figures

2.1	Bosch Key Technologies enabling automated driving	6
2.2	Levels of Autonomous driving according to SAE	6
2.3	Automation steps for autonomous driving	7
2.4	Basic setup of ADAS system	8
2.5	Bosch sensors for automated driving	8
2.6	Types of LiDAR systems	10
2.7	Travel time measurement	11
2.8	"Soft" object (fog)	12
2.9	LiDAR main components	12
2.10	Automotive LiDAR manufactures worldwide	16
3.1	Motorized spinning scanner	20
3.2	Light sending and receiving a) Sending light path b) Receiving light path	20
3.3	Schematic of the PCB stack and laser	21
4.1	Initial model exterior geometry	25
4.2	Final 3D model	26
4.3	Final 3D model subsystems of LiDAR	27
4.4	LiDAR: (a) Rotating housing and (b) Static support	27
4.5	The interaction between function, material, manufacturing process and geometry	28
4.6	Main Chassis	29
4.7	Bottom holder assembly	30
4.8	PCB board geometry	31
4.9	The two parts of the PCB holder identified in Blue and Red	32
4.10	Laser holder	33
4.11	Laser Spacer	34
4.12	Optics chassis	35
4.13	Insulation part 3D model	36
4.14	Optics holder	37
4.15	Optics parts assembly in the global model	37
5.1	Change of focus position	40
5.2	Range of conventional heat transfer modes	41
5.3	Main chassis: a) Representative annular fins array; b) dimensions for the annular fins	43
5.4	Efficiency of annular fins of rectangular profile	44
5.5	2D Schematics of LiDAR sensor	44
5.6	Free convection boundary layers on the lateral surface of short vertical cylinders	45
5.7	Mini fans location	50

5.8	Setup for TE-0820 Board temperature monitoring	51
5.9	Location of the thermocouple on TE0820-03 Board	52
5.10	FPGA Temperature monitoring	52
5.11	Setup	53
5.12	Temperature with time for CoLID laser	54
5.13	Temperature with time for the 1000mV without fan.	54
5.14	Temperature distribution on the simplified μ mirror controller board with MAR2100 component	56
5.15	Temperature distribution on the simplified CoLID laser	57
5.16	Temperature distribution on the simplified TE0208 board	58
5.17	Temperature distribution for the $T_i=26^\circ\text{C}$	59
5.18	Temperature distribution for the $T_i=85^\circ\text{C}$	59
5.19	Temperature distribution for the $T_i=-40^\circ\text{C}$	60
5.20	Heat transfer mechanics on the laser source.	61
5.21	Heat transfer mechanics on the FPGA.	61
5.22	Heat transfer mechanics on the MAR2100.	61
5.23	Temperature distribution for the system with no rotation.	64
6.1	SLA fabricated parts.	68
6.2	Top and bottom holders: CNC machined parts.	68
6.3	Laser holder and spacer: CNC machined parts.	68
6.4	Optic holder: CNC machined part.	69
6.5	PCB holder: Combined CNC machined and wire EDM	69
6.6	Main chassis: Combined CNC machined and wire EDM	69
6.7	PCB board used in the prototype.	70
6.8	Cork part.	70
6.9	Fan assembly on one of the two parts of the PCB holder	72
6.10	Fan assembly on the second half of the PCB holder.	72
6.11	PCB assembly on one of the two parts of the PCB holder	73
6.12	PCB holder assembly	73
6.13	Bottom holder assembly.	73
6.14	Laser holder assembly.	74
6.15	Laser holder assembly on the PCB holder.	74
6.16	Assembly on the main chassis	75
6.17	Laser spacer assembly.	75
6.18	Optics chassis assembly	76
6.19	Cork part assembly.	76
6.20	Optics chassis assembly	77
6.21	Top holder assembly.	77
6.22	Final assembly	78

List of Tables

2.1	Comparison of different types of sensors	9
2.2	Operating temperatures range	15
2.3	LiDAR Benchmark of some brands	16
3.1	System main requirements	23
4.1	PCB's latest version	32
4.2	Possible material choice for final LiDAR device	35
4.3	Summary of <i>Accura 25</i> material properties	35
4.4	Properties AM40 cork	36
5.1	Correlation equations for vertical cylinders in natural convection	46
5.2	Convective heat transfer correlations from a horizontal rotating cylinder	47
5.3	Values used for heat transfer coefficient calculation	48
5.4	Convective coefficient and heat transfer for each convective effect	48
5.5	UF3F3-500 Sunon mini Fan main specifications	50
5.6	Materials defined for the thermal simulation	55
5.7	Heat sources power consumption and power dissipation	58
5.8	Heat source average temperature for each initial temperature	60
5.9	Heat source average temperature for the initial ambient temperature of 70°C.	60
5.10	Heat transfer on the heat sources.	62
5.11	Temperatures for the system with and without fans.	63
5.12	Temperatures for the system with and without fans.	64
5.13	Surface temperature by numerical simulation for rotational and non-rotational system.	64
5.14	Analytic calculations considering the numerical temperatures for the rotational and non-rotational systems.	65
6.1	Manufactured parts details.	71
6.2	Standard parts.	71

Abbreviations

Acronyms

ADAS	Advanced Driver Assistance Systems
AM	Additive manufacturing
AMCW	Amplitude Modulated Continuous Wave
APDs	Avalanche Photodiodes
ASTM	American Society for Testing and Materials
AV	Autonomous Vehicle
CAD	Computer-Aided Design
CNC	Computer Numerical Control
CTE	Coefficient of Thermal Expansion
EDM	Electrical discharge machining
EMC	Electromagnetic compatibility
EMI	Electromagnetic interferences
FEUP	Faculdade de Engenharia da Universidade do Porto
FMCW	Frequency Modulated Continuous Wave
FoV	Field of View
FPGA	Field-Programmable Gate Array
HFoV	Horizontal Field of View
IC	Integrated Circuit
ISO	International Organization for Standardization
LiDAR	Light Detection And Ranging
MEMS	MicroElectroMechanical System
PCB	Printed circuit board
PCM	Phase change materials
Radar	Radio Detection And Ranging
SAE	Society of Automotive Engineers
SLA	Stereolithography
SWIPT	Simultaneous Wireless Information and Power Transfer
TEC	Thermoelectric cooler
TIM	Thermal Interface Material
ToF	Time of Flight
VFoV	Vertical Field of View

Symbols

β	Volumetric thermal expansion coefficient (1/K)
η_f	Fin efficiency
ν	Kinematic viscosity (m ² /s)
ρ	Density (kg/m ³)
ω	Rotational velocity (rad.s ⁻¹)
A_f	Fins surface area (m ²)
A_t	Area of the fins and the exposed portion of the base (m ²)
c_p	Specific heat (J/kg-k)
D	Diameter (m)
g	Gravitational acceleration (m/s ²)
Gr_D	Grashof number for diameter
h	convective coefficient (W/ m ² K)
H	Height (m)
k	Thermal conductivity (W/m.K)
N	Number of fins in the array
$\overline{Nu}$	Nusselt number
Q_{cond}	Heat transfer by conduction (W)
Q_{conv}	Heat transfer by convection (W)
Q_t	Total heat transfer rate (W)
Ra_H	Rayleigh number for height
Pr	Prandtl number
Re_D	Reynolds number for diameter
Re_r	Rotational Reynolds number
T_{airi}	Average fluid temperature inside the system (°C)
T_C	CoLID global component average temperature (°C)
T_F	FPGA global component average temperature (°C)
T_i	Initial temperature (°C)
T_M	MAR2100 global component average temperature (°C)
T_s	Surface temperature (°C)
T_∞	Temperature for free stream conditions (°C)
V	Linear velocity (m/s)
W_e	Electric power consumption (W)

Chapter 1

Introduction

1.1 Context

This work composes the master thesis for the conclusion of the Master's degree in Mechanical Engineering at FEUP, specialisation of Production, Conception and Manufacturing.

Such thesis was made under the scope of an internship at Bosch Car Multimedia in Braga, inserted at the project Sensible Car (SC). The project has several tasks, with high level of independence, allowing the parallel execution of the activities.

1.2 Overview of the company

Bosch was founded in 1886 by Robert Bosch as "Workshop for Precision Mechanics and Electrical Engineering" in Stuttgart [1].

Nowadays, Bosch is considered one of the most innovative companies in the world being distributed in 150 countries (including sales and partners also), with 40300 associates represented mainly in four business areas: Mobility solutions, Industrial technology, Energy and Building Technology and Consumer Goods [1].

In Portugal, Bosch has three production plants in Aveiro, Braga and Ovar, and a sales center in Lisbon.

Braga unit is the main plant for Car Multimedia division, and the largest Bosch company in Portugal, having started its activities in 1990. In 2018, a new technology and development center opened, also in Braga, for the business unit Chassis System Control (CC).

1.3 Motivation and goals

As autonomous-vehicle (AV) technology progresses from driver assistance to full autonomy, driverless cars are looking more likely to become a reality. Thus comes significant benefits, including increased personal safety, time saving for drivers, mobility for nondrivers, decreased environmental harm, and reduced transportation costs. It will also lead to drastic shifts in value chains, profit

pools, and needed capabilities (for example, software expertise or cybersecurity) that could introduce entirely new industries within automotive. A recent McKinsey survey also suggests that car buyers are becoming even more interested in Advanced Driver Assistant System (ADAS) applications that promote comfort and economy, such as those that assist with parking or monitoring blind spots [2].

In order to achieve reliable autonomous vehicle, it is required a high precision and complex system involving many different disciplines, which have led to developments in sensors such as the LiDAR. The need for high quality and precision in the majority of the components and the complexity of the system itself, is one of the reasons why LiDARs are so expensive. The global autonomous vehicle market size was projected to be valued at \$54.23 billion in 2019, and is projected to garner \$ 556.67 billion by 2026, registering a compound annual growth rate of 39.47 % from 2019 to 2026 [3].

This thesis involves a depth study of knowledge and technologies related to the various scientific, technical and industrial domains required to acquire skills and capabilities for the design and development of a LiDAR system, which involves evaluating the benefits and risks inherent to the implementation of the technologies studied. Bearing in mind that automotive industry has regulations that cover every device installed in a vehicle such as the standard for electronics, mechanical systems, software and optics, that regulates the environmental conditions experienced during manufacture, shipping, handling, storage, vehicle assembly and maintenance. Such conditions and tests are within the scope of ISO 16750, which defines a set of rules and tests that automotive sensors should follow, covering electrical, mechanical, thermal, climatic and chemical loads.

The output of this thesis is to define a small and low-cost rotating housing concept for LiDAR sensor with application in autonomous driving mainly for highway pilot which should fulfill the automotive industry standards. The focus will be an housing mechanical system, which should be thermally stable and mechanically robust for long-term operation ensuring hermetic properties (IP rating) to the system because the electronic and optical components will change their performance when submitted to different thermal loads. For the validation of the prototype, thermal and structural simulation performance (temperature and vibrations) will be performed

1.4 Thesis content

The thesis is divided into distinct chapters, as follows:

- Chapter 1 - Introduction: A short presentation of the Bosch company is performed as well as the project where the internship was inserted. The motivation of the study and the main objectives of this thesis are also on the scope of this chapter;
- Chapter 2 - State of the art: Contextualization of the automotive LiDAR in autonomous driving, automotive standards and the LiDAR benchmark are performed;

- Chapter 3 - System requirements and specifications: regarding the optics, electronics and housing chassis for the Bosch LiDAR sensor are presented;
- Chapter 4 - Prototype development: the created parts will be analysed by function, material, geometry and manufacturing process;
- Chapter 5 - Thermal management: solutions applied to the system including analytic calculations, experimental tests and numerical simulations are presented;
- Chapter 6 - Functional prototype: prototype materialization and assembly sequence;
- Chapter 7 - Conclusions and future work: conclusions about the developed prototype and possible future work that can be pursued are described;

Chapter 2

State of art

2.1 Autonomous driving

Autonomous driving is becoming the next big digital disruption in the automotive industry. However, the possibility of integrating autonomous driving vehicles into current transportation systems not only involves technological issues but also requires the acceptance and adaptation of users. Autonomous driving is motivated primarily by the following desires [4]:

- Reducing number and severity of crashes - Approximately 1.35 million road deaths each year and many other serious injuries are caused by traffic accidents. Adaptive cruise control systems, for example, improve the traffic flow and make a major contribution to avoiding accidents [5];
- Improved fuel economy - Improvement of 23% to 39% in highway fuel economy [6];
- Using travel time for entertainment and work - Freeing up the billions of hours spent annually by people driving their cars. 56 minutes per day may be freed up for other uses [6];
- Greater Independence - Allow mobility for all ages once the over-65 group is growing twice as fast as others [6].

Bearing in mind this motivation for autonomous driving, figure 2.1 shows, according to Bosch, the elements that are necessary to be aware when it comes to have an automated vehicle; in another words, key technologies that allow full autonomous driving. For example, fully autonomous cars can make thousands of decisions for every kilometer traveled, which they need to do so correctly and consistently.

2.1.1 Autonomous driving levels

With the growth of driving assisted systems, introduced over the years in motor vehicles, autonomous driving is becoming a reality. With the purpose of clarifying manufacturers and users, the

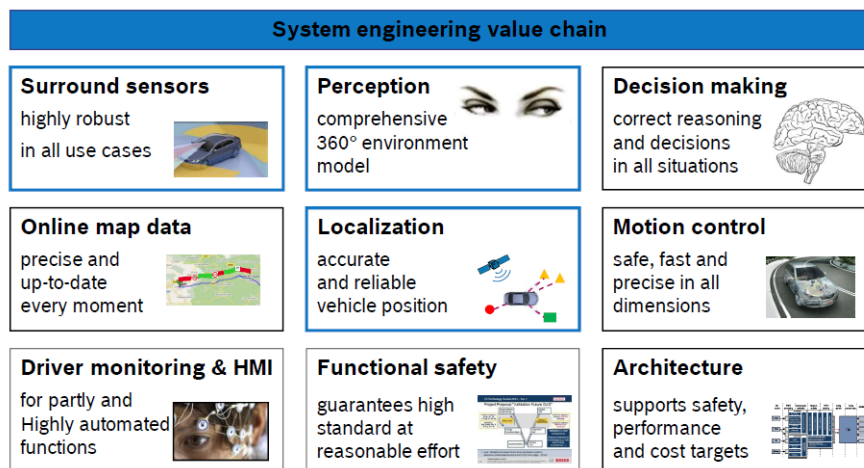


Figure 2.1: Bosch Key Technologies enabling automated driving [6].

Society of Automotive Engineers (SAE) [6] introduced in 2014 the concept of autonomy levels: from 0 to 5, where zero are vehicles with no level of automation and 5 completely autonomous, as shown in figure 2.2.

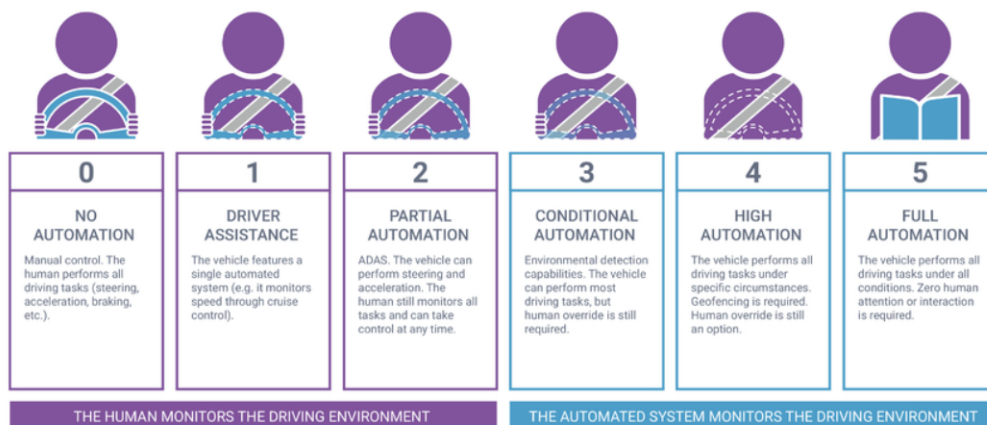


Figure 2.2: Levels of Autonomous driving according to SAE [7].

Level 0 is where the driver controls everything, including steering, brakes, throttle, and power.

Level 1 has most functions still controlled by the driver, however with the option that key functions such as steering or acceleration can be performed automatically.

Level 2 enables the car to perform more than one automated function at the same time, supported by additional contextual information. The driver can be disengaged physically from operating certain functions of the vehicle.

Level 3 enables drivers to completely shift safety-critical functions to the vehicle, under certain conditions. The driver must still be ready to intervene.

Level 4 represents the beginning of fully autonomous vehicles, with the vehicle performing all safety-critical driving functions, while monitoring road conditions for a complete trip. The

limitation is that the vehicle cannot be relied upon to operate in this way for all road scenarios or weather conditions.

Level 5 is achieved when the autonomous vehicle's performance is equal to that of a human driver, except in certain more extreme environments [4].

Regarding all automation levels presented above, some features are necessary to increase the degree of automation according to each driving surroundings such as: lane keeping support, traffic jam assist, highway assist, highway pilot and urban automated taxi. In figure 2.3 these steps and some specifications about each one, making driving a safer and easier experience are presented.



Figure 2.3: Automation steps for autonomous driving [6].

Although some manufacturers have introduced many new advanced-driver-assistance-systems features, such as automatic braking and adaptive cruise control, highly autonomous vehicles—in other words, level 4 cars—are not expected to hit the road until sometime between 2020 and 2025. According to McKinsey & Company, in 2030 is expected that 35 percent of cars sold will have conditional automation (level 3) and 15 percent will have high automation (level 4). The exact growth trajectory will depend on multiple factors, including improvements in core technologies, pricing, consumer acceptance of self-driving cars, and the ability of manufacturers and suppliers to address fundamental concerns about safety and the potential for hacking [2].

For self-driving cars on fourth and fifth level, LiDAR is an important tool for monitoring and mapping the surroundings of the vehicle.

2.1.1.1 Advanced Driver Assistant System (ADAS)

Advanced Driver Assistance System (ADAS) is considered as a subset of Driver Assistant System (DAS) that preforms driving tasks. The difference between DAS and ADAS, is that ADAS uses

complex processing algorithms to detect and evaluate the vehicle environment based on data collected by a variety of sensor inputs, figure (2.4), which increases the traffic safety and efficiency improving the sustainability of the vehicle [8].

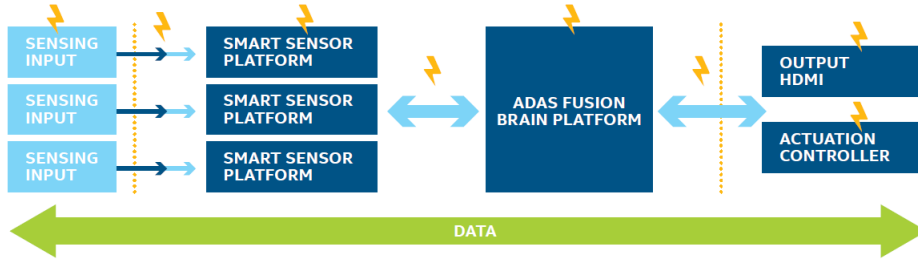


Figure 2.4: Basic setup of ADAS system [8].

Another advancements in ADAS design is the concept of sensor fusion which is the theory of using multiple sensory technologies (LiDAR, radar, ultrasonic sensors and cameras) to generate an accurate and reliable map of the environment around a vehicle [9, 10]. In addition to the technologies complementing each other, it is also important to have sufficient overlap in order to increase redundancy leading to an improvement in safety.

Figure 2.5 shows the Bosch vision where a combination of different sensors ensures a full 360 degrees field of view: long- and mid-range radars, stereo-video and near-range cameras, ultrasonic sensors and a LiDAR. In the next subsection, advantages and drawbacks of each one will be presented.

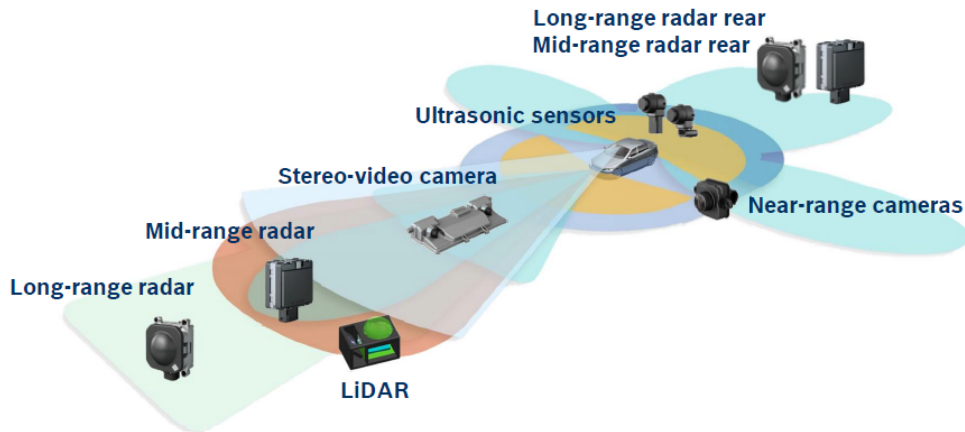


Figure 2.5: Bosch sensors for automated driving, according to Bosch.

2.1.2 Sensors for autonomous driving

Demand for ADAS is caused by the desire to build safer vehicles and roads in order to reduce the number of road fatalities and by legislation in the leading countries [8]. By taking advantages of each sensor, it is possible to create an accurate long- and short-range map of a vehicle's

surroundings under a vast range of weather and lighting conditions [10].

Ultrasonic sensors are primarily used for short-range object detection because ultrasound waves suffer from strong attenuation in air beyond few meters [10]. So, this sensors can be used to measure parking spaces while the vehicle is in motion, and detect vehicles driving in an adjacent lane [5].

Cameras are a cost-efficient and easily available sensor; however, they require significant processing to extract useful information and depend strongly on the ambient light conditions [10]. For instance, they are used to recognize lane markings, traffic signs, traffic lights, and other road users [5].

Radar sensor sends out radio waves that bounce off objects and return to the receiver and as this waves are the largest in the electromagnetic spectrum, it is difficult to differentiate between objects. Radar lends itself well to long-distance object detection but is not typically very precise.

LiDAR has higher angular resolution. The angular resolution of these systems makes it possible to identify the horizontal and vertical position of a car or pedestrian more precisely, and to distinguish different objects which are located at a same distance and moving with same speed. On the other side, this system tends to loose performance under bad weather conditions, such as rain, fog or ice [11]. This technology will be discussed later on. In the table 2.1 some parameters of the different types of sensors that can be used in ADAS are presented.

Table 2.1: Comparison of different types of sensors [12].

	Camera	Radar	LiDAR	Ultrasonic
Object detection	●	●	●	●
Object classification	●	●	●	●
Distance estimation	●	●	●	●
Object-edge precision	●	●	●	●
Lane tracking	●	●	●	●
Range of visibility	●	●	●	●
Functionality in bad weather	●	●	●	●
Functionality in poor lighting	●	●	●	●
Cost	●	●	●	●
Production readiness	●	●	●	●

● Good ● Fair ● Poor

2.2 LiDAR sensor

Dating back to sonar and radar, LiDAR (Light Detection and Ranging) is an advanced sensor transmitting information via laser. With the birth of the laser in 1960, LiDAR appeared firstly in 1971 used for Lunar surface mapping during Apollo 15's mission, and being later used in archaeology and agriculture mapping. Only in 2005, LiDAR first appeared in automotive [13].

This technology can take several different forms as reflected in the LiDAR classification presented below.

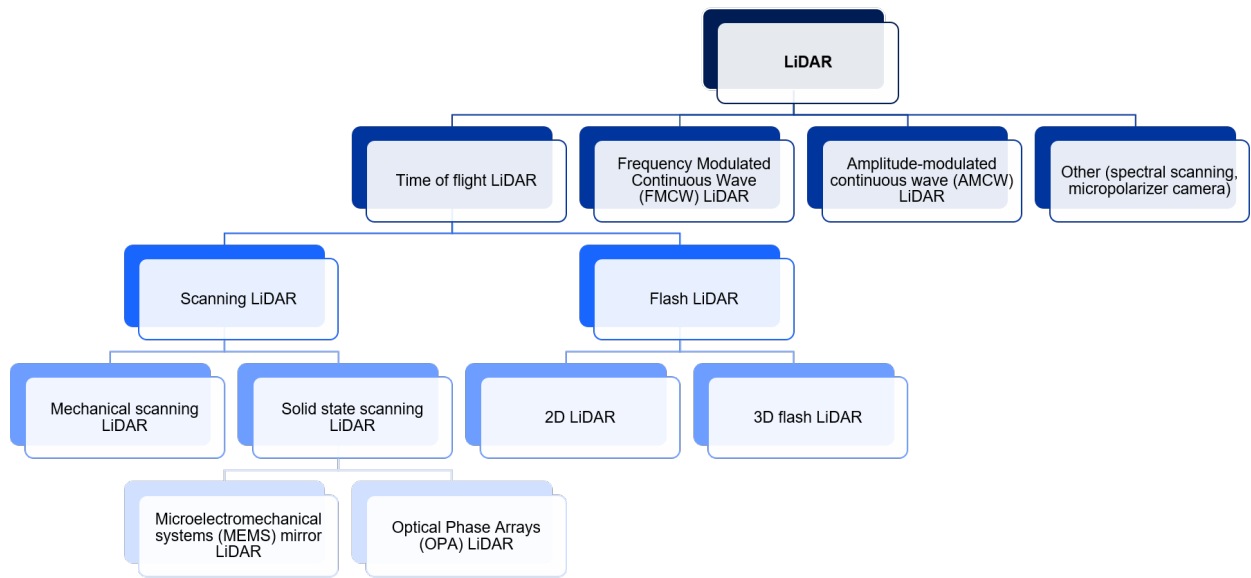


Figure 2.6: Types of LiDAR systems [11].

Mechanical scanning LiDAR has the advantage of 360-degree coverage in horizontal. It is possible to stick one LiDAR unit on the top of a car and get a complete view of a car's surroundings.

Solid state LiDAR, in contrast, are fixed in place and typically have a horizontal field of view of 120° or more. It takes at least four units to achieve comparable 360° degrees coverage with a solid-state sensor.

Flash LiDAR illuminates the entire field with a single flash. Current flash LiDAR technologies use a single wide-angle laser. This can make it difficult to reach long ranges since any given point gets only a small fraction of the source laser's light.

FMCW LiDAR measures distance and velocity simultaneously based on beat frequencies using up-down frequency ramps, immune to background light, but requiring more computational power [9].

AMCW LiDAR applies a periodic amplitude modulation to an otherwise continuous optical beam and the modulation on the received signal is compared to that on the outgoing signal in order to infer the relative time shift between the two [14].

In following subsections a detailed study about time-of-flight LiDAR regarding its main working principle as well as the main components that are generally used will be made. At the end some details about the LiDAR technology that are already in the market will be presented.

2.2.1 LiDAR operating principle

Automotive LiDAR is a technology similar to RADAR but instead of using microwaves, measures the distance by using laser (infrared (IR) or near-infrared (NIR)). It is a critical component for autonomous vehicles which is used to recognize pedestrians, street lighting poles, and roads by processing point cloud data, using a very high sampling frequency through a single transmitter/receiver [4, 9].

For the majority of the devices distance is estimated by measuring the time of flight (TOF). LiDAR sensor sends light pulses from the transmitter to the environment, and when it reaches an object, it is reflected and sent back to the receiver. When the pulse is emitted the time-digital-converter (TDC) starts counting the time and when the pulse is received the TDC stops. Through this time, it is possible to measure the object distance by :

$$d = \frac{c \times t}{2} \quad (2.1)$$

where,

d = distance (m);

$c \cong$ speed of light (3.0×10^8 m/s);

t = time (s).

Since the emitted light pulse travels twice the distance between the sensor and detector, the time between sending and receiving is twice the distance of the object (figure 2.7).

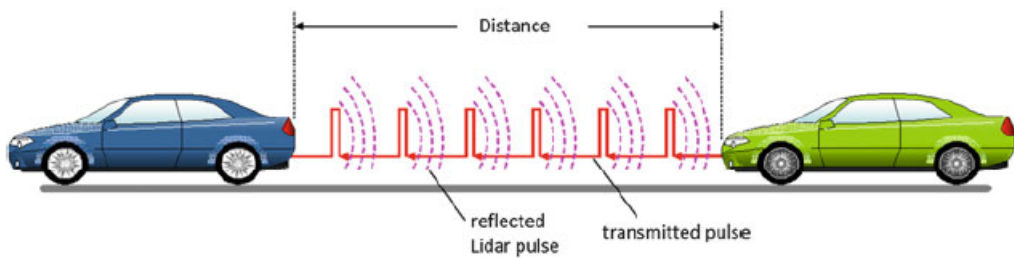


Figure 2.7: Travel time measurement [4].

On other hand, if there is an increased attenuation of the atmosphere due to fog, rain, etc., then individual pulses are attenuated in the air, which can lead to a decrease in the pulses power and consequently having a lower range (figure 2.8). Depending on the optical design of the system, for example, if the wavelength of the pulse is 1550nm, the attenuation is higher when compared to pulses of 905nm [4].

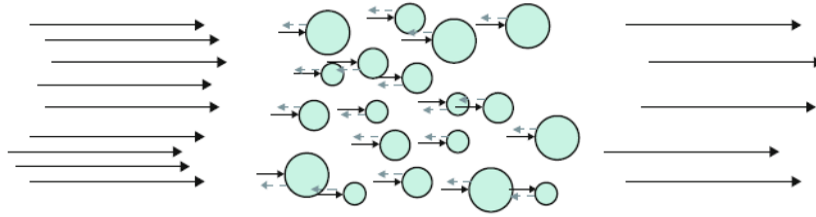


Figure 2.8: "Soft" object (fog) [4].

The field of view (FoV), the range and eye safety are very important parameters of a LiDAR system as they will be the main responsible for ensuring a safe autonomous driving [6]. FoV is defined as the projected angle covered by the sensor. Range defines the maximum object distance that sensor detects. Eye safety is the maximum power without damaging the eyes.

2.2.2 LiDAR main components

In figure 2.9 a schematic of a possible LiDAR system configuration is presented. The main components or group of components that stand out are: the sending unit, the receiving unit and the glass cover.

As shown in subsection 2.2.1, the LiDAR system will emit a laser beam, which when reflected by an object in the defined range and FoV, will be detected by a photodetector. The distance to the object that reflected the beam is estimated from the measurement of the time of flight (TOF) of the beam [9].

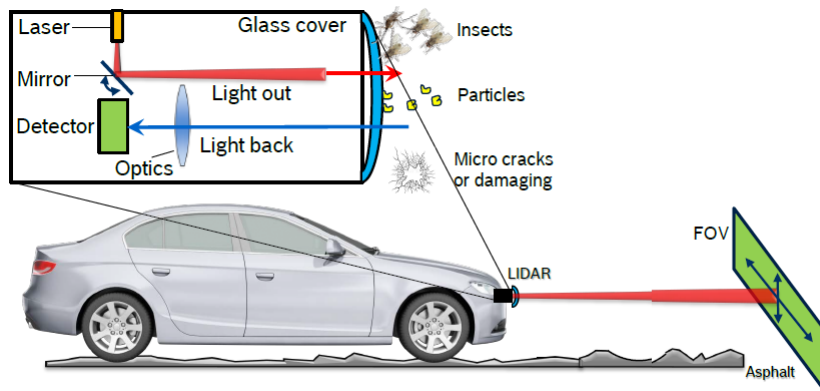


Figure 2.9: LiDAR main components [6].

Light source

LiDAR requires a pulsed laser (Diode, Vertical-cavity surface-emitting laser (VCSEL) or Fiber laser) capable of producing laser pulses a few nanoseconds long and with a high repetition rate. The typical wavelength used are: 850, 905, or 1550 nm [14, 11]. One of the most important reasons of choice is the eye safety as mentioned in subsection 2.2.1.

Fluid in the human eye is transparent to light at 850 and 905 nm, allowing the light to reach the retina at the back of the eye. If the laser is too powerful, it can cause permanent eye damage. The main advantage of using these wavelength is that the detectors can be built using cheap, ubiquitous silicon technologies.

On the other hand, the eye is opaque to 1550 nm light, allowing 1550 nm LiDAR to operate at a much higher power level without causing retina damage. Higher power levels are related to a longer range. Nevertheless, while this wavelength lasers at 1550 nm can operate at higher power levels without a risk to human eyes, those higher-power levels can still cause other challenges. Building a LiDAR based on 1550 nm lasers, in contrast, requires the use of exotic, expensive materials like indium gallium arsenide [14].

Optical system

The optical system is a set of optical elements (that includes lenses, mirrors, prisms, etc.) for the emission and reception parts of the sensor. This system influences the range, the FoV and the intensity of the received signal.

Photodetector

Photodetector is an optoelectronic device which generates an electrical signal when illuminated. The photodetectors need to be sensitive to the chosen wavelength.

For 905 nm LiDAR, silicon avalanche photo diodes (SiPDs), single-photon avalanche diodes and silicon photo-multipliers (SiPMs) are popular detectors, each with its specific advantages and limitations. For 1550 nm lasers, mostly InGaAs photo-diodes or avalanche photodiodes (APDs) are used [11].

Scanning system

The optical scanning system is used to control the direction (vertical and horizontal) of the laser beam. A rotating polygon mirror, MEMS μ Mirror or a rotating housing with several lasers stack, are methods applied for scanning the sensor surroundings. The scanning system steers the light at certain directions (azimuthal and elevation), sets system resolution and defines the speed at which images (frame rate) are generated.

Data processing and control System

It is an electronic system that controls the light source and scanning system, reads and processes signals from the photodetector and sends this information to other interfaced devices.

Housing and chassis

It is a mechanical support for all the LiDAR sub-systems. This component keeps all the parts in the correct position and controls the thermal and vibrational conditions of the entire sensor. This sub-system usually includes cleaning systems and constitutes the mechanical protection of the LiDAR.

2.2.3 ISO automotive requirements

The development and production of a LiDAR sensor must fulfil the requirements imposed by automotive industry standards. The requirements based on these standards are on the document ISO 16750 (International Standards Organization) which describes the potential environmental

stresses that electric and electronic devices will face when mounted on a vehicle, specifying the tests and requirements that the device must fulfil [15]. This document, under the general title *Road vehicles — Environmental conditions and testing for electrical and electronic equipment* is composed of the following parts:

- Part 1: General [15];
- Part 2: Electrical loads [16];
- Part 3: Mechanical loads [17];
- Part 4: Climatic loads [18];
- Part 5: Chemical loads [19].

Regarding the third part, the mechanical load tests described in ISO 16750-3 are applied to the device accordingly to its mounting location on the vehicle. The device must withstand several vibration tests and mechanical shock tests [17]. The enclosure material must be resistant and the interior structure must be robust enough to keep the correct optical alignment.

According to ISO 16750-4 standard, electronic devices must also function properly for external operating temperatures that depend on mounting location [18]. Regarding the table 2.2, the minimum functioning temperature for most of the possible mounting locations is -40°C and the maximum required temperature varies between 70°C and 160°C . As LiDAR's most probable mounting location will be on the exterior or in cavities (can be attached to the body, frame, door or lid), it will correspond to code E and according to the standard it corresponds to recommended operating temperature range between -40°C and 75°C . Nevertheless, for safety reasons, temperature requirements range was increased from -40°C to 85°C (which corresponds to code G) [18]. Materials should be selected considering these range of temperatures.

The devices installed on vehicles are exposed to contaminants and must not be affected by them. ISO 16750-5 describes the laboratory tests that determine if the temporary exposure to chemical agents unacceptably affects a device [19]. The enclosure material must be chemically inert to the contaminants identified by this standard.

The degree of protection that the enclosure provides for the electrical device against water, foreign objects and access is described by International Protection code, IP code. This code related to the protection of electrical equipment installed on a road vehicle is described by ISO 20653 [20]. The enclosure material must be watertight and mechanically resistant enough to deliver a sealed structure.

Table 2.2: Operating temperatures range [18].

Code	Minimum operating temperature T_{min} (°C)	Maximum operating temperature T_{max} (°C)
A	-20	65
B	-30	65
C	-40	65
D		70
E		75
F		80
G		85
H		90
I		95
J		100
K		105
L		110
M		115
N		120
O		125
P		130
Q		140
R		150
S		155
T		160
Z	As agreed upon	

2.2.4 LiDAR benchmark

Regarding subsection 2.1.1 LiDAR is critical for achieving the levels 4 and 5. Some studies prove that around 80 to 100 companies are working in automotive LiDAR developments [21]. The automotive manufacturers are evolving to cope with the changing market dynamics and collaborating with the tech giants to achieve the goals of self-driving cars. The players such as General Motors, Waymo, Uber, and Apple are engaged in developing their own self-driving vehicles.

In the market there are some LiDAR Systems top sellers such as Velodyne, Ouster, Continental Automotive, LeddarTech, Ibeo Automotive, Valeo, Quanergy and many others. Figure 2.10 presents some companies worldwide that are considered as automotive LiDAR manufactures.

Velodyne's LiDAR has emerged as the leading developer, manufacturer, and supplier of 3D real-time perception systems used in a variety of commercial applications including autonomous vehicles, vehicle safety systems, 3D mobile mapping, 3D aerial mapping, and security [23]. Regarding automotive LiDAR systems, most part of them are time-of-flight mechanical scanning including new 128-laser-*Alpha Prime* and *Ultra Puck*. Velodyne is also producing a solid-state lidar called the *Velarray* [11].

LeddarTech is a company that produces solid-state LiDAR designs which are used for the development of high-resolution solutions for automotive autonomy and security, as well as for drones, industrial vehicles and transportation systems [24].

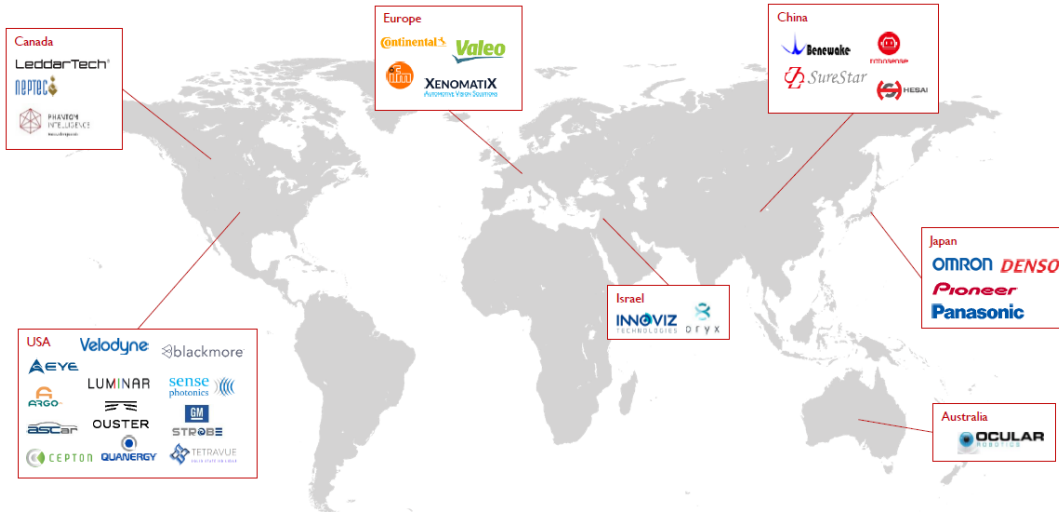


Figure 2.10: Automotive LiDAR manufactures worldwide [22].

Ibeo Automotive Systems has established itself as a worldwide leader in LiDAR sensor technology and the associated software tools. Ibeo has set itself the goal of reinventing mobility by turning vehicles into cooperative partners and thus making road traffic safer [25].

Ouster builds high-resolution lidar sensors for use in autonomous vehicles, robotics, and many other applications, using its unique multi-beam flash LiDAR design [26]. Just like Velodyne, it sells units with 16, 64, and 128 lasers, but with an integrated design that has the potential to dramatically reduce the cost and complexity of manufacturing LiDAR units. Ouster's most sophisticated LiDAR is the OS-2 with 128 channels and uses the principal of TOF mechanical scanning.

In the following table (table 2.3) some specifications of a few LiDAR systems in the market are presented.

Table 2.3: LiDAR Benchmark of some brands [26, 23, 25, 24].

Company	Velodyne		ibeo Automotive	Ouster	LeddarTech
Model	Ultra Puck™	Alpha Prime™	ScaLa B3	OS2	M16R-75J0010
Picture					
Vertical Field of View [°]	40	40	3.2	22.5	3
Horizontal Field of View [°]	360	360	145	360	99
Horizontal Angular Resolution [°]	0.1-0.4	0.1-0.4	0.25	-	-
Vertical Angular Resolution [°]	0.33	0.11	0.8	0.18	-
Weight (g)	925	3500	510	445	182
Range [m]	200	245	0.25-85	240	6-30
Operating wavelength (nm)	903	903	905	865	905
Operating temperature (°C)	[-20,60]	[-20,60]	[-40,85]	[-20,50]	[-40,85]
Estimated price (\$)	-	100,000	250	24.000	895

As presented in the table, LiDAR cost is very high mainly in rotation LiDARs such as presented by Velodyne and Ouster. Although Solid-state LiDARs, in contrast, are fixed in place and

typically have a field of view of 120° or less, it takes at least various units to achieve comparable coverage with a solid-state sensor, so the cost will be higher.

Not much is known regarding the mechanical chassis and the thermal management solutions that are used in each LiDAR on the market. On other hand, according to subsection [2.2.3](#), some of the LiDAR systems presented in the market are not able to fulfil automotive temperature requirements.

Chapter 3

System requirements and specifications

After a benchmark study in order to find out the typical specifications of such devices which are already available in the market, it was possible to define the main requirements for the prototype. Therefore, some of the standards that the LiDAR device must obey include: measurement, resolution, utilization, functioning, manufacturing and industrialization requirements. In the following sections the system requirements are divided by: optical, electronic and housing requirements.

It is important to fully define such requirements in order to serve as goals to achieve in the new product development. Industrialization requirement is the one that demands to fulfill all the standards related to automotive industry. For the prototype production the industrial manufacturing methods were not chosen by due to their cost and time consuming. However it is mandatory in future series production.

3.1 Optical system

Bosch LiDAR system will have its main application as Highway Pilot. Regarding the field of view, the main goal is to provide a 360° horizontal FoV and 12° vertical FoV. To ensure these parameters, the rotation of the LiDAR around itself will assure the 360° horizontal FoV coverage (figure 3.1). A 1D micro-mirror is used to project the signal emitted by the laser in vertical lines, which therefore will be responsible for the vertical FoV (figure 3.2a). In this way, the motorized scanner along with the 1D micro-mirror is part of the scanning system of Bosch LiDAR system.

In the reception there is a 1D array of ADPs which will receive the beams reflected by the objects, shown in figure 3.2b. It is important to notice that the emission optical path and the optical path for the reflected beam are different which means that the LiDAR system is Bistatic (figure 3.1).

The angular resolution is intended to detect objects as small as 400 mm at 180 meters away. For this it is necessary to have a resolution of 0.1° in both horizontal and vertical axis and the distance accuracy has to be smaller than 0.1 meters (accuracy). The 180 meters detection range was determined in order to provide a 5 seconds response when the vehicle drives at 130 km/h, allowing the vehicle to safely stop in case of a steady object at 180 meters away.

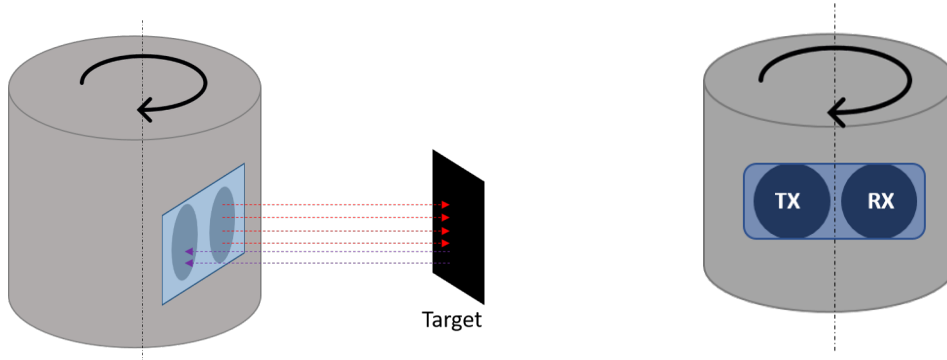


Figure 3.1: Motorized spinning scanner.

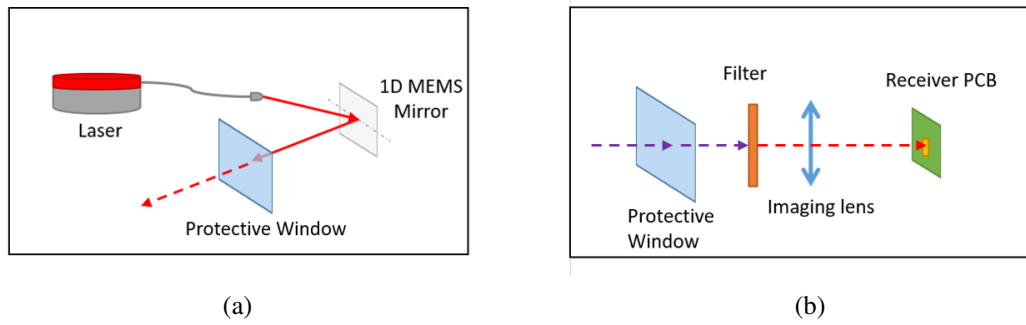


Figure 3.2: Light sending and receiving a) Sending light path b) Receiving light path.

3.2 Electronic components

For the electronic components it is foreseen that a stack of five Printed Circuit Boards (PCB) should be integrated: TE0820-03, carrier board, receiver, μ mirror controller and Simultaneous Wireless Information and Power Transfer (SWIPT) and above this stack, the laser should be implemented.

A PCB mechanically supports and electrically connects electronic components using conductive tracks, pads and other features etched from one or more sheet layers of copper laminated onto and/or between sheet layers of a non-conductive substrate. Components such as integrated circuits (ICs), diodes, transistors, resistors, and capacitors are included to perform a certain task and are generally soldered onto the PCB [27].

Each PCB board of the stack are connected using connectors and the laser is linked to the stack also using connectors, which means that the distance between each component is defined by the height of the connectors, as it is presented in the figure 3.3. It is important to take into account that the connectors are the highest component on each board.

3.2.1 Laser

The CoLID series 1550nm short pulse fiber laser from Connet Laser Technology Co., Ltd. (Shanghai, China) is a fiber laser source delivering high peak power and high pulse energy. It is an ideal

fiber laser source for LiDAR, telemetry and range finding. This laser has a temperature controller integrated, lower power consumption and it is a compact system ($\phi 90 \times 23.5$ mm) despite its high cost. CoLID is a Class IV ¹ laser output product with high risk.

Regarding the operation and usage, the most important requirement for the laser is the eye safety. As previously mentioned at subsection 2.2.2, the laser beam must not be visible and harmful to the human eye. The laser radiant power used is also an important factor to take into account, not only for safety purposes but also for range detection, reason why in Bosch's concept a 1550 nm fiber laser is intended.

Figure 3.3 displays a schematic of the layout of each PCB, the laser and their connections between each other.

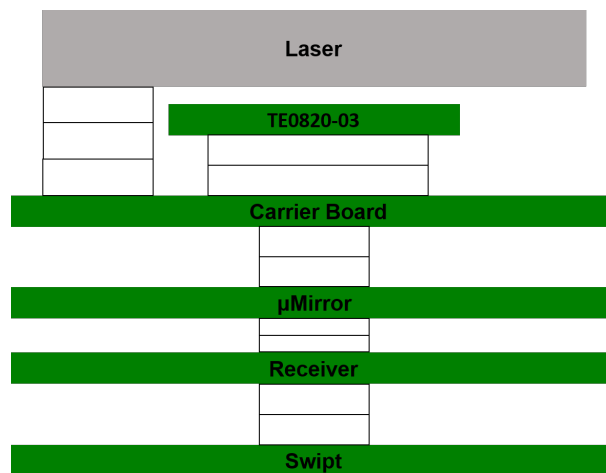


Figure 3.3: Schematic of the PCB stack and laser.

3.3 Housing chassis requirements

Bearing in mind the ISO automotive requirements in subsection 2.2.3, and in order to assure an optimal reliable performance of the LiDAR device, the essential requirements with respect to the housing design that must be taken into account are:

- Hermetically sealed to prevent the entrance of dust, water and other impurities, which can affect the device performance;
- Thermally managed to assure a specific range of temperatures in the housing's interior for a specific range of environment temperatures;
- Shielded from electromagnetic internal and/or external interferences;

¹Lasers are classified for safety purposes based on their potential for causing injury to humans' eyes and skin. The classes can be: I, II, IIIa, IIIb or IV, where the first two classes are relatively safe for eye exposure and the last two are hazardous.

- Mechanically robust for long-term operation, mechanical impacts and “vibrations proof” to maintain the device integrity and function/optics performance;
- Chemically inert to contaminants.

Materials and geometry need to ensure that there is no water, dust and other types of waste inside the housing in order to promote the best operation possible. The IP rating chosen for this prototype is IP67 that requires (according to the standard) protection from dust and water ingress while being immersed up to one meter depth for 30 minutes.

In the housing will be integrated the cleaning system as well as the protective window. The protective window will have the function of protecting the internal optical components from several potential pollutant materials that might stick to it, including dust, mud and insects. At the same time, and perhaps the main function of the protective window, is to ensure good emission and reception of all the laser signals emitted without creating optical aberration when those signals cross the protective window material. The cleaning system should be designed to provide an effective cleaning of the protective window external surface [28]. Nevertheless, it is expected that the housing dimensions should not exceed 120 mm diameter and 200 mm height and must accommodate all the optical components: sending unit, receiving unit, cleaning system, all PCB, electric connectors, cables and thermal management solutions.

The operating temperature should be between -40°C to 85°C . The temperature variations are mainly affected: externally by the environmental conditions and internally by the type of materials used in the housing structure and heating sources. The heating sources are associated with the specific components used and their operation relations. Those issues will be addressed in the chapter 5.

Electromagnetic shielding occurs by the reduction of the electromagnetic field in a space by blocking the field with barriers made of conductive or magnetic materials.

In the following table (table 3.1) a summary of the main specifications of the system is presented.

Table 3.1: System main requirements.

System Overall specifications	FoV (H x V)	360° x 12°
	Angular Resolution	0.1°
	Range	180 m
	Frame rate	10 Hz
	Dimensions (D x H)	120 x 200 mm
	Operating Temperature	-40° to 85°C
Scanning Sub-System	Scanning based	1D μ Mirrors
	Light Source	Fiber laser
	Wavelength	1550 nm
Mechanical Chassis, Housing and Cleaning Sub-System	Hermetically sealed	
	Chemically inert to contaminants	
	Mechanically robust	
	Electromagnetic compatibility (EMC)	

Chapter 4

Prototype development

In the last chapter, we described the specifications and requirements for the Bosch LiDAR to be implemented on a car. In this prototype, as the aim is to be a proof of concept, some requirements are no longer in scope.

For the cleaning system, it is expected to be accommodated on a fixed support (non-rotational), which will cause a decrease on the horizontal FoV from 360° to 300° because 60° will become a blind spot where all the cleaning system components will be placed.

For the requirements directly related to the chassis: hermetically sealed, chemically inert to contaminants, mechanically robust and electromagnetic compatibility they will be pursued whenever possible, however they will not be the goal for this prototype.

4.1 Housing layout

The development of this prototype sensor takes into account the initial geometry proposed by the company, presented in figure 4.1 and the system requirements summarized in table 3.1, which at a prototype level not all of them are possible to fulfil, but it is important to be aware of them. This was the starting point for the project progress.

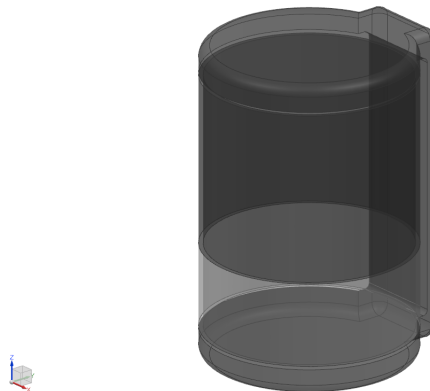


Figure 4.1: Initial model exterior geometry.

The prototype geometry was dependent on components definition. Only after knowing all the specific hardware to be used in the LiDAR system, it was possible to optimize the housing design to fulfil all the objectives and requirements defined. After several iterations, which will be focused in the following sections and subsections, the final 3D CAD model exterior design is presented in figure 4.2.

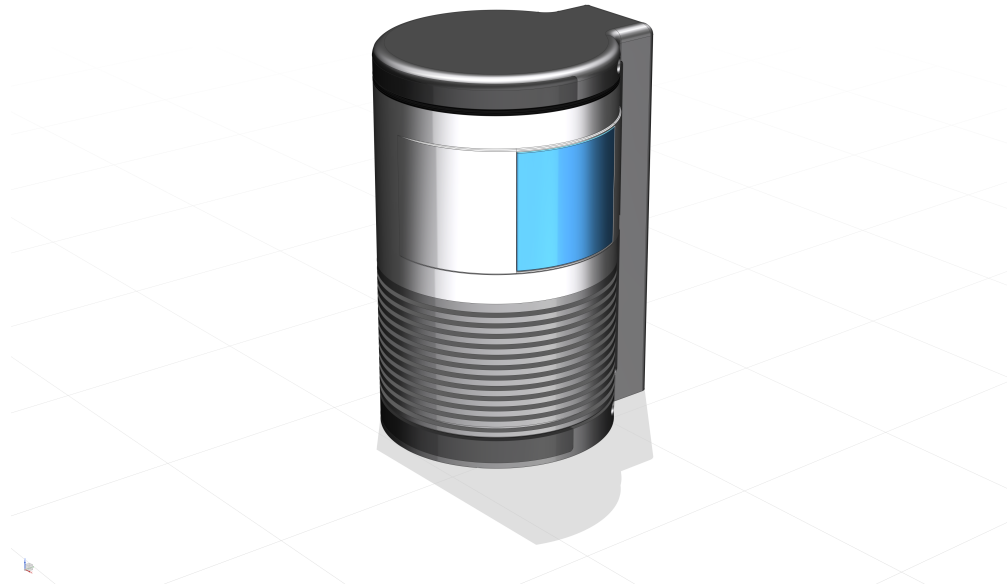


Figure 4.2: Final 3D model.

In a generic way, this prototype could be separated into different systems and subsystems. In the figure 4.3 a side view of the final CAD model is presented where some areas are highlighted:

- A) Cleaning system: will be responsible for cleaning the protective window allowing the performance of the system;
- B) Scanning, Optical and Receiving sub-systems: will hold the 1D μ Mirrors optical elements (lens) and photodetector board;
- C) Data handling and Advanced processing: contains the PCB stack, the COLiD laser and thermal management solutions. This zone is the main focus of this work.
- D) Wireless Data and Power Transfer system: will be responsible for coupling the motor, bearing and the encoder which will grant the rotating movement.

To fulfill the requirement of the 300° of horizontal FoV, the sub-system C must rotate relatively to a static support. In this way, it is possible to differentiate a static support (figure 4.4b) responsible for providing stability and robustness besides holding inside the Cleaning system (A)

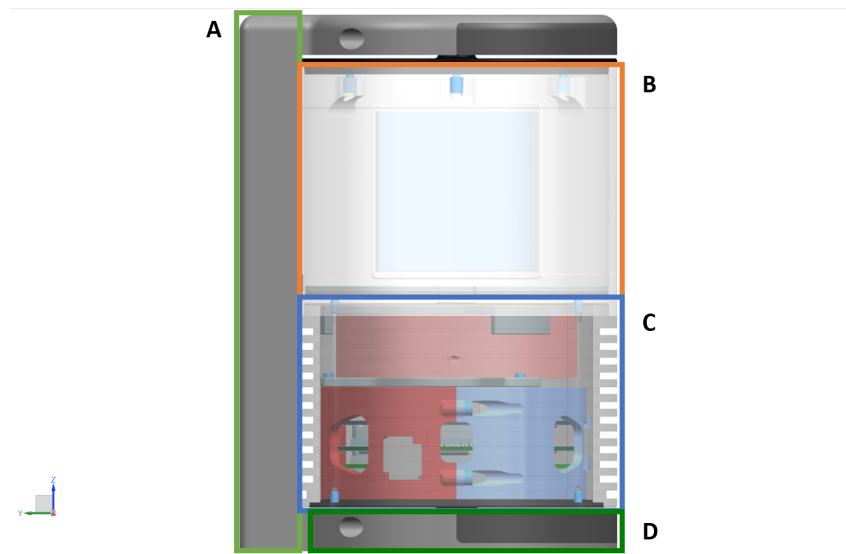


Figure 4.3: Final 3D model subsystems of LiDAR.

and the Wireless Data and Power Transfer system (D). The rotating housing (figure 4.4a) allows the 300 degrees of horizontal FoV coverage and at the same time holds the Scanning, Optical and Receiving sub-systems (B), the Data handling and Advanced processing (C) and also the protective window. It was decided that the sub-system B should also rotate to be easier to implement thermal management solutions.

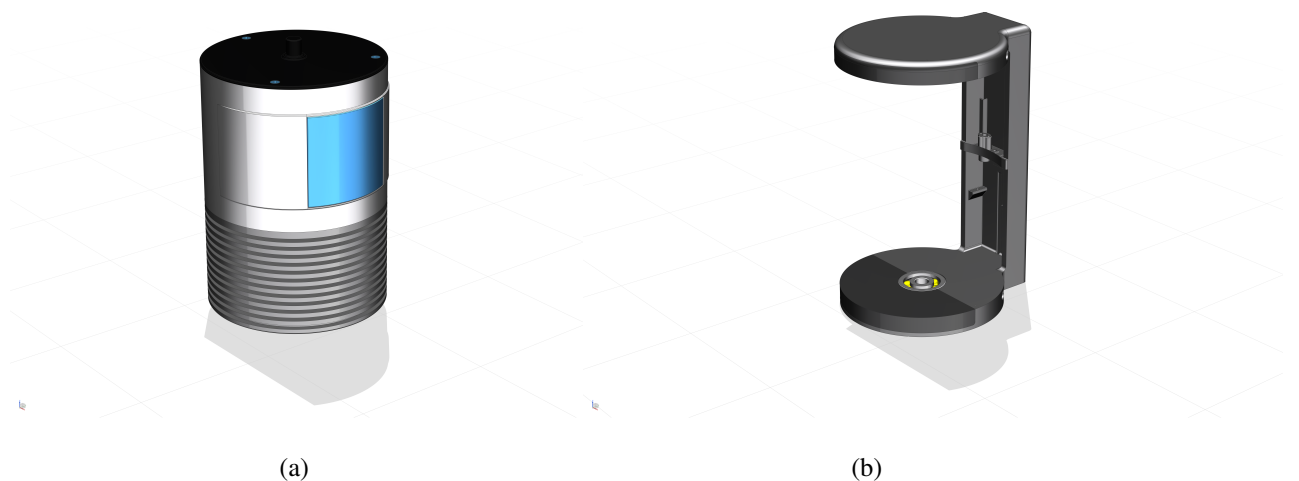


Figure 4.4: LiDAR: (a) Rotating housing and (b) Static support.

In the next subsections will be presented the parts which compose this prototype mainly the geometry explanation, material and manufacturing process choice for prototype production as well as the function of each part.

4.2 Design, material, process, and geometry

According to the graphic of figure 4.5, the selection of a material cannot be separated from part's function geometry and manufacturing process. The part function dictates the choice of both material and geometry. The process interacts with geometry and material choice. The geometry is defined by the part's function, the material, and the manufacturing process [29].

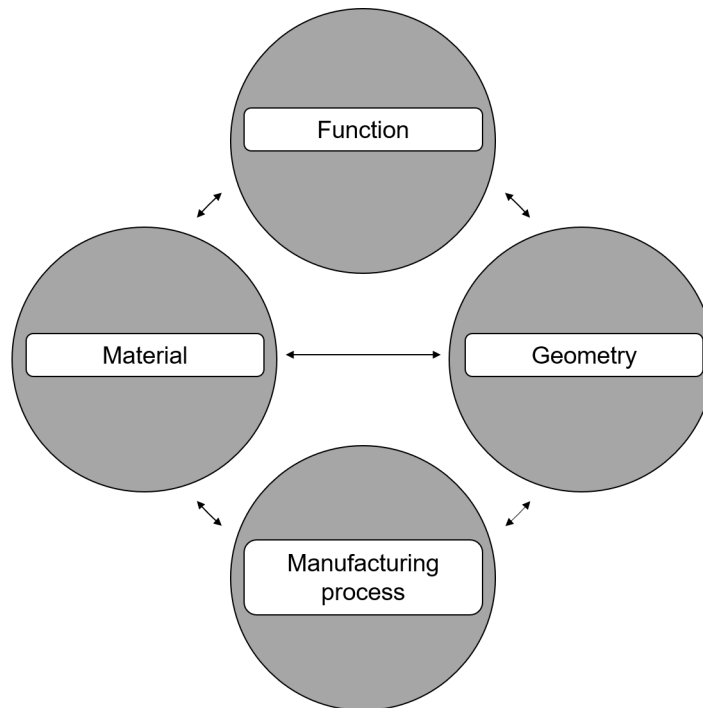


Figure 4.5: The interaction between function, material, manufacturing process and geometry. Adapted from [29].

Material properties: the most important and common properties to take into account for this proof of concept and to build a functional prototype are:

- Tensile strength;
- Failure strain;
- Elastic modulus;
- Thermal conductivity;
- Density;
- Toughness;
- Service temperature;
- Cost;
- Processability.

For each designed part some of these properties stand out, which means that some properties are prioritized in relation to others.

Geometry: Should be chosen according to each application bearing in mind the material properties and the manufacturing processes' specifications such as minimum wall thickness, precision, cost, time.

Manufacturing process: the manufacturing method should allow developing a functional prototype. Processes such as machining, additive manufacturing, and others were taken into consideration.

Function: the parts can have various functionalities such as: holder, chassis, spacer.

4.2.1 Main exterior Chassis

For the main exterior chassis, the material and the geometry need to ensure that there is no water, dust, and other types of waste inside the housing to promote the best operation possible. The part should be robust as it will be exposed to some (not extreme) mechanical loadings and due to several other components being supported in such part. This part will be in permanent contact with the environment.

As regards geometry, regarding issues of assembling and disassemble issues, it was decided that the bottom and top parts are distinct components. So, for that, it was created a polymeric part for the top (subsection 4.2.3) and a holder for the bottom (subsubsection 4.2.1.1) and should be fastened using screws to the main chassis.

Figure 4.6 presents the 3D CAD model of the main chassis.

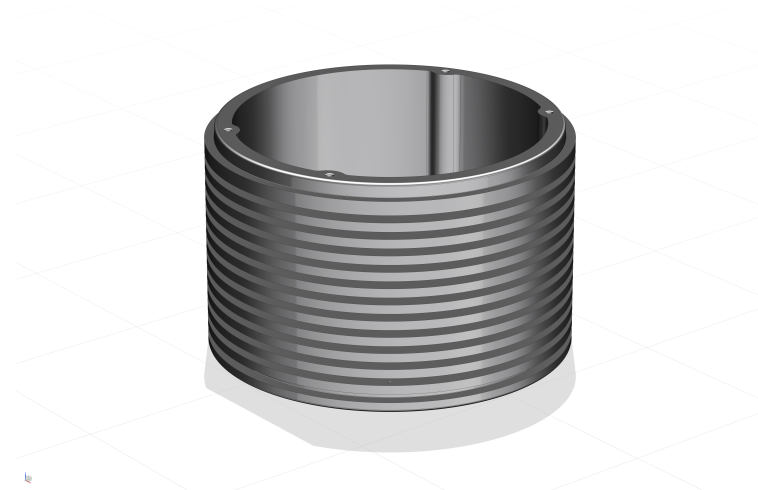


Figure 4.6: Main Chassis.

As this part will rotate, there will be heat transfer by forced convection so, it is expected that the convective coefficient increases on the outer surface of this part. To increase even more the heat dissipation, the exterior surface was filled with annular fins, increasing the surface area, rising the heat transfer. The fins sizing and heat transfer estimation are presented in Chapter 5. Concerning the choice of the material, its conductivity should be high (to take better advantage of the fins) and the mechanical properties must be good for robustness. So, the material should

be metallic and due to cost issues and density a good choice is an aluminium alloy: AW 6082 (Appendix C).

According to the geometry, function and the material, the manufacturing process most suitable to fabricate this part is machining.

To provide the perfect sealing, this will be the hermetical sealing of the system; the installation of sealants should be applied between some parts in future applications.

4.2.1.1 Bottom holder

This part will be located on the bottom of the main chassis (subsection 4.2.1) and connected to it using bolts to ensure that the systems remain closed. Besides, the PCB holder (subsection 4.2.2) will be placed and fixed (also by screws fasteners) on the top of it.

On the shaft of this component a bearing will be coupled, which will allow the movement of the housing along with the frameless motor, encoder and coils. However these elements are not on the scope of this work.



Figure 4.7: Bottom holder assembly.

When choosing the right material for this part, it was taken into account the mechanical properties, which should be good enough to allow the LiDAR's rotation, as well as flat enough since the PCB holder (subsection 4.2.2) will settle on the top surface of such part. So, for the same reasons as the material choice on the last subsection, here aluminium AW 5083 (Appendix C) is also considered and the manufacturing process is machining. The main difference between the AW5083 and AW6082 is the offered products: AW6082 is offered as round bars and AW5083 in form of laminated plates.

4.2.2 PCB holder

The main purpose of this part is to fix the PCB stack, so this was very dependent on the board's geometry, especially the location of the holes for fastening and the disposition of some of the

electronic components on the board, which was not decided during the initial phases of the development of this system as it is an iterative process which involves several teams working simultaneously.

The final version of the board's geometry was decided to be circular (diameter 90 mm) with three tabs with holes (3,2 mm) at 120 degrees, as it is presented on figure 4.8.

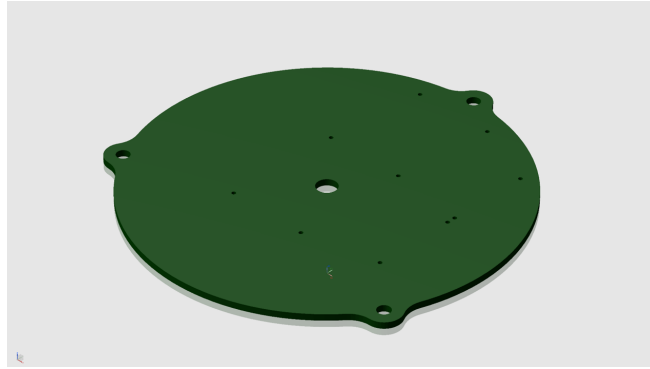


Figure 4.8: PCB board geometry.

Four of the five PCBs have the same board geometry, figure 4.8, whereas the other PCB has a different geometry and dimensions, being rectangular as presented in table 4.1 and will be connected to the carrier board. In the table 4.1 is presented the electronic components on their latest version. It is possible to notice that some of them are not on the final version yet.

Despite the PCBs being connected by connectors, it is not enough to ensure the right position of the stack. To lock the vertical movement of the PCBs slots in the chassis were created with the same shape and height as the board extensions. The horizontal movement is locked by using three screws passing through all the aligned PCB fixation holes.

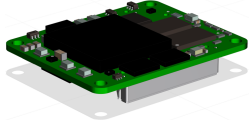
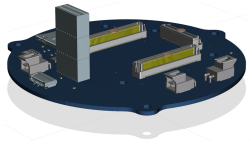
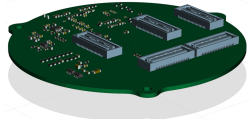
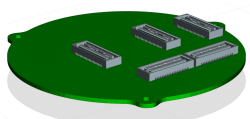
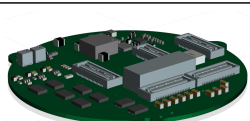
In a first approach it was thought about having 3 parts at 120 degrees each one supporting one of the board extensions however the assembly could be more difficult as it was required more screws. In a second approach, it was decided that this chassis should be divided into 2 parts (180 degrees) to provide easier assembly and the parts are simpler, as it is shown in figure 4.9.

These two parts have also the function of holding the three fans: there are two extensions for each fan on these parts allowing bonding the fans using an adhesive. The fans specifications will be addressed in the next chapter 5.

The holes were created around the parts to make the components lighter, as well as for thermal management due to the fans cross flow and due to the rotation that creates a forced convective effect.

In line with the material choice for the main chassis (subsection 4.6), Aluminium AW6082 was chosen again mainly for the high thermal conductivity, being manufactured via machining.

Table 4.1: PCB's latest version.

Image	Name	Main component	Version
	Laser source: CoLID laser	-	Final version
	TE0820 Board	FPGA	Final version
	Carrier Board	Not defined	Final version
	μ mirror	MAR2100	Final version
	Receiver	Not defined	First version
	SWIPT	Not defined	Intermediate version

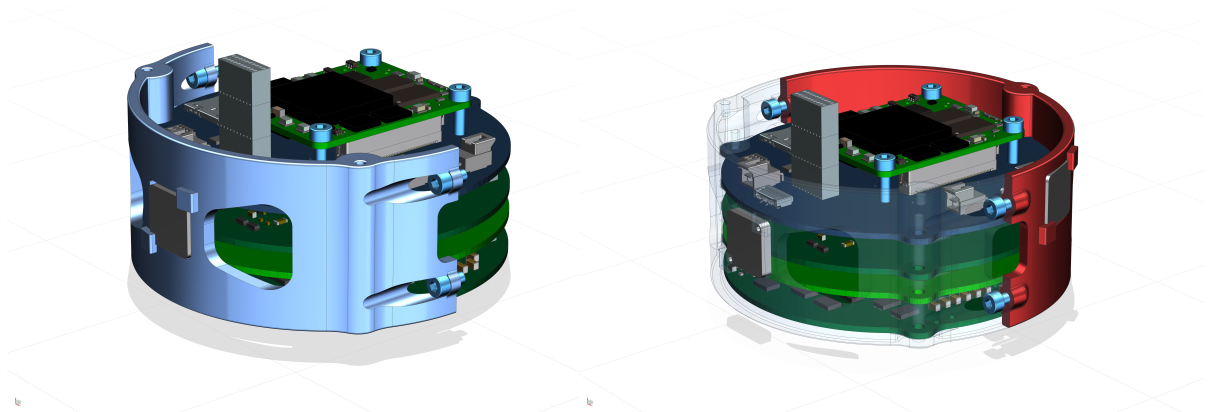


Figure 4.9: The two parts of the PCB holder identified in Blue and Red.

4.2.2.1 Laser holder

Above the PCB stack, the CoLID laser must be linked to the carrier board using connectors. The detachment may occur on this connector as they are not enough for a perfect fit between both

components, as it happened on the board to board connectors on the PCB stack.

So, to provide greater robustness and to avoid laser displacement, this laser holder was created. In the assembling process, first is necessary to fix the laser to this part by screws in the specific threaded holes that already exist in the laser (figure 4.10a) and afterwards, these two parts are assembled on the system where the laser holder is fastened to the PCB chassis (section 4.2.2) in three points separated in 120 degrees (figure 4.10b).

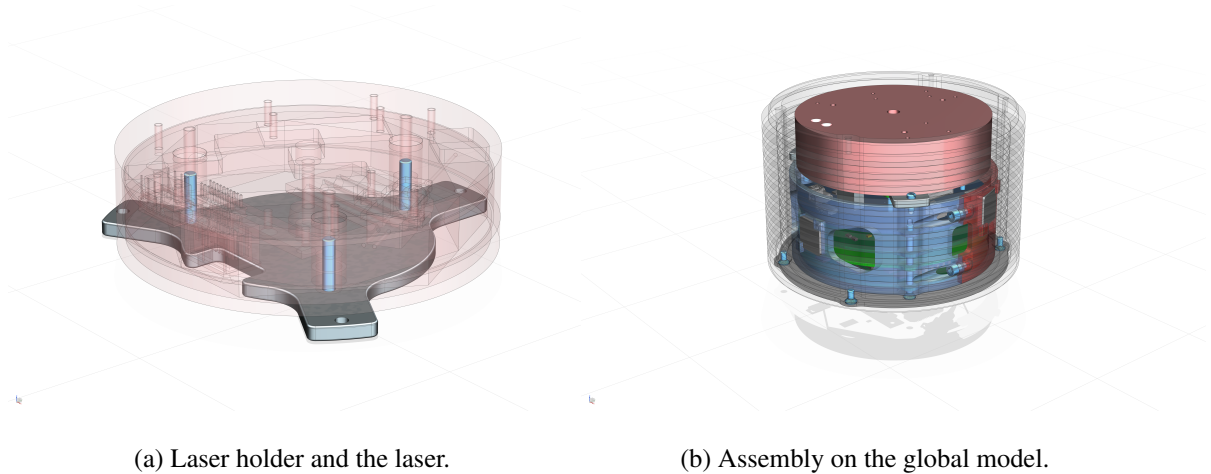


Figure 4.10: Laser holder.

Besides being a structural part, the laser holder also works as a thermal bridge between the laser and FPGA (a component of the TE0280 PCB) and the exterior housing. That is why the material selected for this application is aluminium AW5083, which will be discussed in the next chapter.

4.2.2.2 Laser Spacer

This part will be on the top of the CoLID laser and screwed to it. The main function is for thermal management, acting as a thermal bridge with the exterior chassis, removing the heat by conduction from the laser to the environment. This issue will be discussed later on. In figure 4.11 the location and the geometry of this part is presented

In this way, the material must have an high thermal conductive, being the AW5083 alloy a good choice due also to the excellent machinability properties.

4.2.3 Optics parts

To insulate the Scanning, Optical and Receiving sub-systems from the Data handling and Advanced processing which generates heat, it was decided to create a set of parts: optics holder, insulation part and the optics chassis. As the Scanning, Optical and Receiving sub-systems were not ready and fully decided by other team members, these parts are provisional and the geometry and material choice could vary for the final LiDAR device.

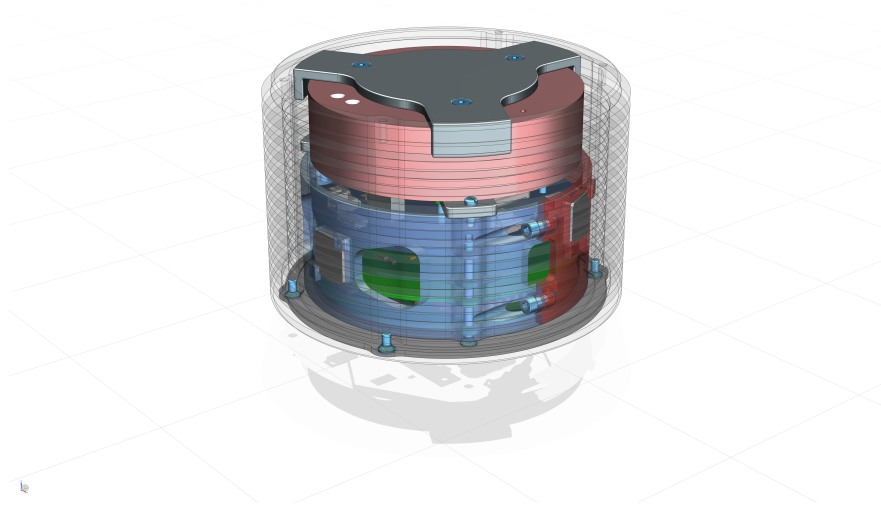


Figure 4.11: Laser Spacer.

The optics chassis will be placed on the top of the main chassis (section 4.2.1) and will be in direct contact with the environment. A list of some of the material properties which should be prioritized for the optical chassis are:

- Low thermal conductivity: separating the region where heat is generated (electronic components) from the region where no heat is produced (optics elements);
- Electrical insulator: allowing insulation of current between the optics elements and the electrical components;
- Service temperature: should fulfil the automotive standards;
- Robust: has to support mechanical loads (not extreme) mainly due to centrifugal forces;
- Low thermal expansion: it is important to consider because changes in the optic's size may influence alignment and stresses on the components.

According to the material properties mentioned above, the material choice for this part falls upon plastics. It was made a research on possible materials that fit on the material's requirements for a possible final LiDAR device. They are mainly thermoplastics and some important properties are summarized in table 4.3.

For the prototype part material, due to its high production speed, resolution and accuracy the manufacturing process most suitable for this part is stereolithography (SLA). The materials for this process have to be photopolymer that are cured by a UV laser. So, to have a functional prototype for the SLA manufacturing process, the selected material was *Accura 25* (Appendix C), which is used for functional automotive mock-ups, which simulates the properties of a durable plastic being a polypropylene - like class.

Table 4.2: Possible material choice for final LiDAR device [30].

	ABS	Polyamida 66	POM-c	PMMA	PC
Elastic modulus (GPa)	1.8-3	1.3-2	2.5-3.2	3.1 - 3.3	2.1 - 2.5
Thermal conductivity (W/m.K)	0.13-0.18	0.13-0.29	0.16-0.3	0.18 - 0.19	0.2 - 0.27
Density (g/cm ³)	1.03-1.07	1.13-1.15	1.39-1.41	1.17 - 1.19	1.18 - 1.24
Electrical resistivity (ω .m)	1.00E+11	1.00E+9	1.00E+11	1.00E+13	1.00E+14
Max. service temperature long (°C)	85-100	170-200	170-200	65 - 90	115 - 130
Thermal expansion (1/K) at 20°C	1E-4	1.5E-4	1.4E-4	1.2E-4	8E-5

In the following table some of the properties of the used material for this part is presented, the rest of properties are presented on the Appendix C. It is important to notice that the thermal properties are not available.

Table 4.3: Summary of *Accura 25* material properties.

	Condition	Value
Tensile Strength (MPa)	ASTM D 638	38
Tensile Modulus (GPa)	ASTM D	1.59-1.66
Elongation at Break (%)	ASTM D 638	13 - 20
Flexural Strength (MPa)	ASTM D 790	55 - 58
Flexural Modulus (MPa)	ASTM D 790	1.380 - 1.660

Concerning the design, it has space for coupling the protective window [28] and will be connected by screws to the main chassis 4.6.

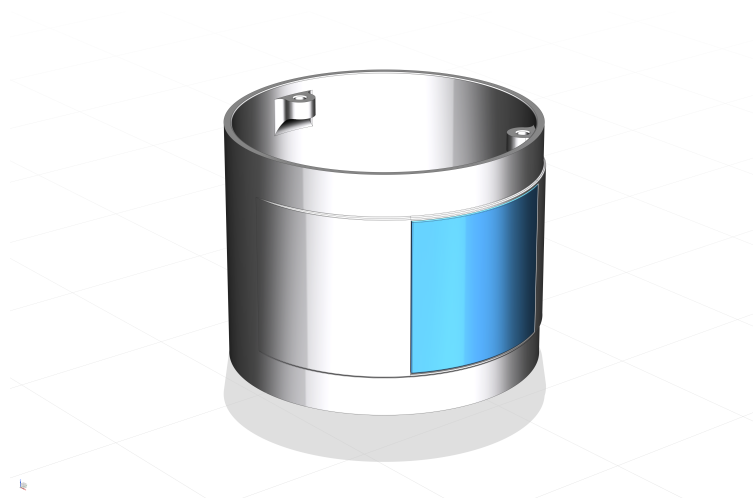


Figure 4.12: Optics chassis.

4.2.3.1 Insulation part

At the top of the optics chassis, to ensure an almost complete insulation of the optical and electronic systems and also to absorb vibrations, it was created an insulation component with the geometry presented on figure 4.13.

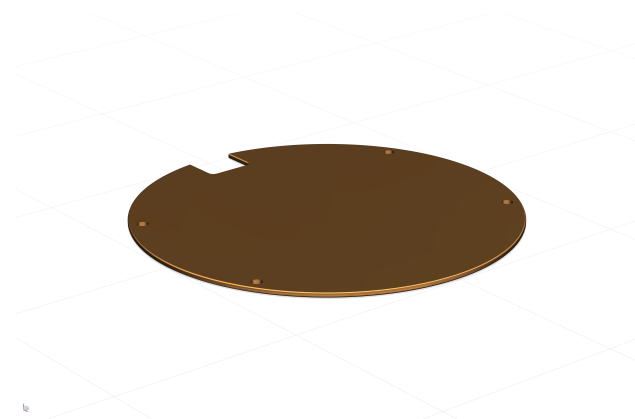


Figure 4.13: Insulation part 3D model.

At an industrial level, a good option for this part is the AM40 cork from *Amorim Cork*, which is used in the automotive industry having high thermal insulation, according to the properties presented on table 4.4. This product is suitable to be bonded using existing industrial adhesives to various substrates for example aluminium alloys.

Table 4.4: Properties AM40 cork [31].

	Condition	Value
Density (kg/m ³)	ASTM F1315	200-250
Tensile Strength (MPa)	ASTM F152	0.4
Stress Compression @ 10% (MPa)	ISO 1856	0.20
Thermal Resistivity (m.K/W)	ISO 8301	21.7

4.2.3.2 Optics holder

On the top of the insulation part, subsection 4.2.3.1, will be placed the optics holder which is created for holding the optics elements such as lens, μ Mirrors, etc. The material choice is the aluminium AW5083 alloy mainly due to its low coefficient of thermal expansion ($1.2\text{E-}5$ - $2.9\text{E-}5$ (1/k) [30]) which is a very important property as the displacement of the optical element can compromise the main functions of the whole device.

Regarding the geometry, it has a hole to allow that the optical fibre laser connector is linked to the optical components, presented in figure 4.14.

The aluminium part and this insulation part will be glued by an adhesive: SikaForce 7710 L100 [32].

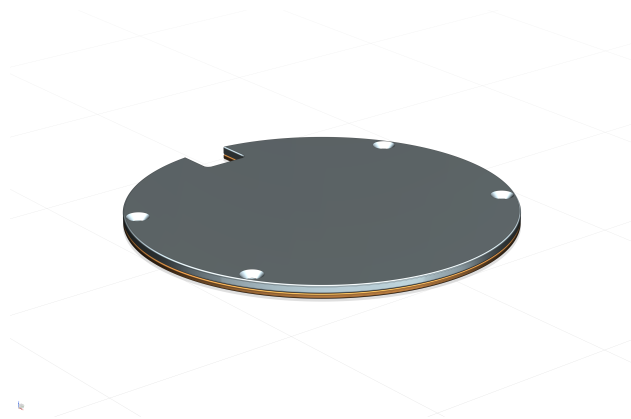


Figure 4.14: Optics holder.

After the Optics holder and the insulation part bonding, they are fixed to the optics chassis [4.2.3](#), and consequently to the rest of the model, using screws as it is presented on figure [4.15](#).

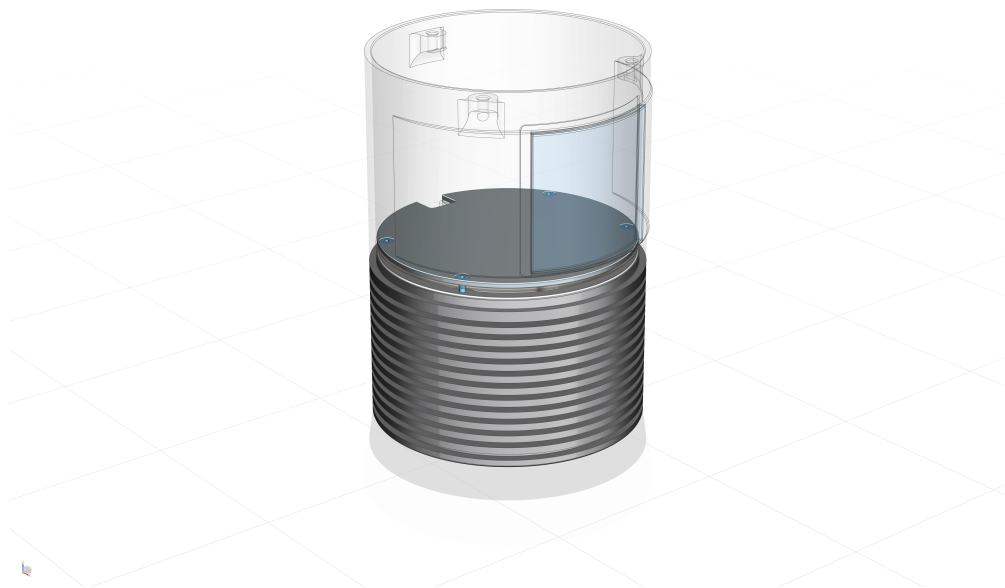


Figure 4.15: Optics parts assembly in the global model.

Chapter 5

Thermal management

As previously mentioned during the past chapters, the electronic components will generate heat during the system operation. When the temperature on the system is outside the operating temperature of each electronic component, it will cause failures. Furthermore, temperature can also cause a decrease in performance of the optical system, mainly negative effects on the receiving and sending lenses.

In this way, temperature control of a LiDAR device must be taken into account to assure the normal performance of the sensor. In other words, cooling and/or heating solutions must be considered.

5.1 Effects of temperature in LiDAR system

All the materials, processes and systems are affected by temperature change in a higher or lower scale. These changes might have a positive or negative influence on the system's performance. During the development of any electronic device, several solutions must be applied to minimize any negative consequences of temperature variation, which can happen due to internal or external factors, such as heat generation from components or environment temperature changes. A LiDAR sensor is not an exception, as it will be exposed to all kind of weather conditions having to withstand automotive standard temperatures (from -40°C up to 85°C) while having the integrated electronics producing heat.

The thermal management of the LiDAR is a crucial topic due to the challenging automotive requirements and the temperature variation that can annul the optics system activity. Optics is one of the most sensitive systems in the sensor, as it can suffer misalignments or loss of optical properties even with minor variations.

The most important key aspects related to temperature and LiDAR components performance that must be addressed during the design process are as follows:

- Decenter and defocus of the optical sending and receiving lenses;
- Changes on the laser wavelength;
- Low performance of the laser;

- Failure on the electronic components.

The next section will address the thermal defocus, as it is the one of the main problems that affects the optics system.

5.1.1 Thermal defocus

Most optical materials undergo a change of refractive index n with temperature T , conveniently quoted as a rate of change $\frac{\partial n}{\partial T}$.

The focal length of a single lens depends on its surface curvature and refractive index. Focal length variation with the temperature depends on the coefficient of linear thermal expansion (CTE) of the lens material. Some optical materials are more sensitive to temperature than others.

The equation 5.1 expresses the focal length variation with temperature of a single thin lens (where f is the focal length, γ is the thermal constant of the optics material, α is the coefficient of thermal expansion of the housing and T is the temperature)[33]:

$$\Delta f = -f \cdot (\gamma + \alpha) \cdot \Delta T \quad (5.1)$$

By this equation, if the change in focal distance due to the housing is equal to the change in focus due to the lens, then the defocus is zero, and the system is considered athermal [34].

In the figure 5.1 it is shown the change in an optical component's refractive index with temperature ($\frac{\partial n}{\partial T}$) which can lead to a shift in a lenses focal length (Δf), changing the focus position.

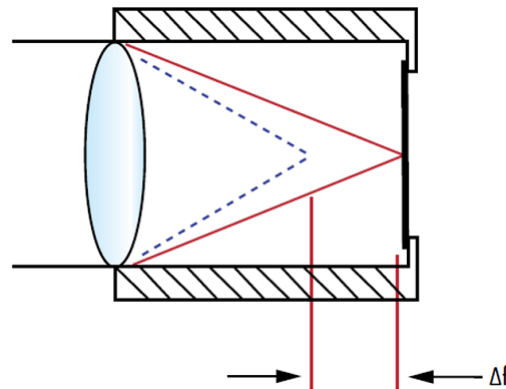


Figure 5.1: Change of focus position [35].

The γ values are higher in optics materials used for infrared systems and in plastic materials, thus it can be concluded that these materials are more sensitive to temperature change [33]. The ability to correct for thermal defocus depends on coefficient of thermal expansion (CTE, α) of the materials and the change in index with temperature ($\frac{\partial n}{\partial T}$) [34].

5.2 Thermal management solutions

It is important to find out thermal solutions to ensure the right performance of the sensor. To this purpose it is important to bear in mind the three mechanisms of heat transfer: radiation, conduction and convection which can be combined for obtaining a thermal management solution. The available solutions can be characterized as passive, active, or a combination of the two (hybrid).

In the following figure, some thermal management solutions are quantified by the heat transferred (W/m^2) between a surface (100°C) and the ambient of 20°C [36].

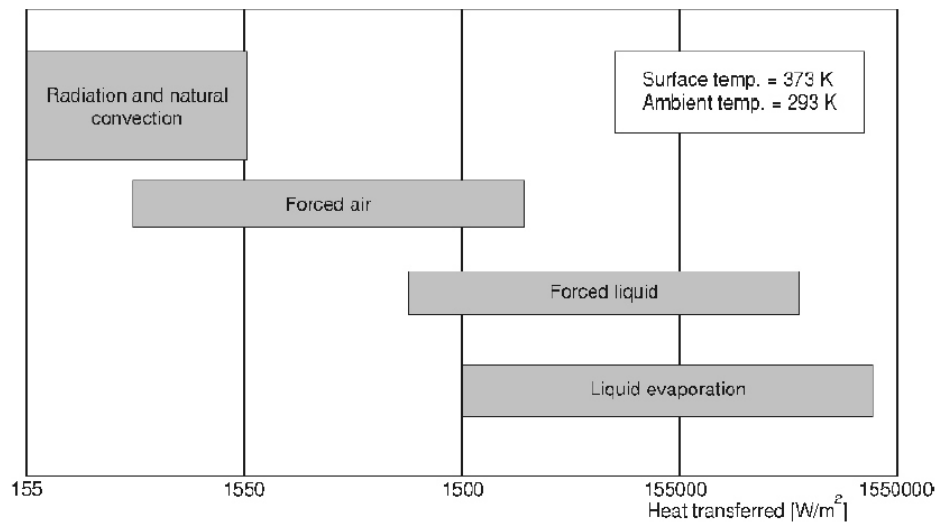


Figure 5.2: Range of conventional heat transfer modes [36].

Passive thermal management solutions

The passive techniques have an absence of external power, being relatively reliable and simple to implement. However, they are performance-limited for many high power applications [37].

On the prototype, the main passive thermal management techniques that were applied include:

- **Thermal bridges:** areas or components of an object which has an higher thermal conductivity than the surrounding materials, creating a path of least resistance for heat transfer, mainly through conduction. In this system, thermal bridges were applied in order to increase the heat transfer between the hot spots in some PCB components and the main chassis and also between the laser and the main chassis;
- **Thermal paste:** which is a thermal interface material responsible for eliminating air gaps or spaces (which act as thermal insulation) from the interface area in order to maximize heat transfer and dissipation. In the prototype, it was applied between the FPGA and the laser holder;
- **Extended surfaces:** generally made in a highly conductive material, are designed to increase the surface area and consequently the heat transference rate by conduction to the

surrounding environment. In the prototype, the creation of a part with exterior fins magnifies the heat transfer due to the increase in the surface area;

- **Housing materials:** Prioritizing the usage of high thermal conductivity material such as aluminium alloys on the components which are in contact with heat dissipation components helps to eliminate hot spots. It was decided to use low thermally conductive materials to insulate the optics from the electronics systems.

Active thermal management solutions

Active thermal management techniques, requiring input power, provide increased performance, but also reduced reliability and added complexity [37]. These techniques have an higher consumption, resulting in higher costs compared to passive cooling air. This type of thermal management solution includes: forced air and liquid convection, microchannels heat sinks and thermoelectric cooler.

Taking into consideration the initial requirement for the operating temperature range from automotive standards, an active cooling solution is required, at least for the “critical” components, while for other electronic components, that can withstand temperatures up to +85°C, passive cooling solutions can be used for heat dissipation.

Only one active solution was applied on the prototype, which was the case of Fans. The fans uniform the temperature distribution through forced convection, and together with passive solutions, effectively could reduce the temperature hot spots.

On the following subsection different thermal management solutions will be analysed, especially for the extended surface which includes analytic calculations.

5.2.1 Extended surfaces

As previously discussed, the main aluminium chassis part (section 4.6) has extended surfaces (fins) around its exterior surface. The fins configuration are considered annular fins with a rectangular profile with the dimensions and geometry presented in figure 5.3. The material chosen was aluminium alloy AW 6082 to maximize the heat transference due to its high thermal conductivity.

The dimensions were selected to maximize the heat transference area and not to restrict the manufacturing processes by the minimum thickness allowed. As the electronic components occupy all the height of the main chassis, the fins were also applied through all the height of the component.

For the analytic calculations regarding the heat dissipation through the fins of the main chassis, some simplifications were considered:

- Steady-state conditions;
- One-dimensional radial conduction in fins;
- Constant properties;
- Negligible radiation exchange with surroundings;
- Uniform convection coefficient over the outer surface (with or without fins).

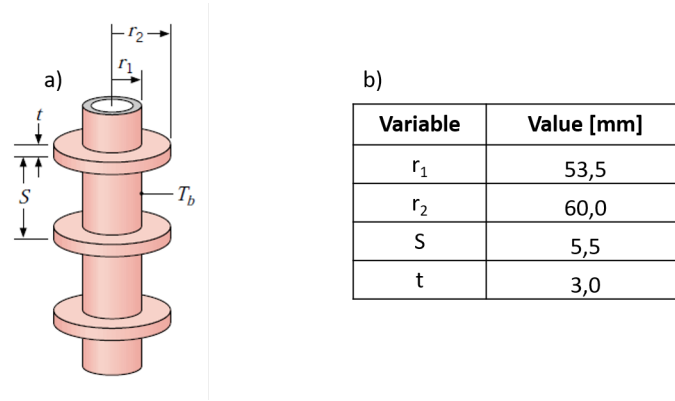


Figure 5.3: Main chassis: a) Representative annular fins array [38]; b) dimensions for the annular fins.

Considering these assumptions, the total heat transfer rate Q_t (W), from the surface area can be computed using the following expressions [38]:

$$Q_t = hA_t \left[1 - \frac{NA_f}{A_t} (1 - \eta_f) \right] (T_b - T_\infty) \quad (5.2)$$

$$A_f = 2\pi (r_{2c}^2 - r_1^2) \quad (5.3)$$

$$r_{2c} = r_2 + (t/2) \quad (5.4)$$

where,

A_t area of the fins and the exposed portion of the base (m²);

A_f fins surface area (m²);

N number of fins in the array;

η_f is the fin efficiency;

h is the convective coefficient (w/m².K);

T_∞ Temperature for free stream conditions (°C).

For the fin efficiency calculation, which characterizes the performance of a single fin, it is possible to obtain the value in figure 5.4, where the efficiency of a rectangular annular fin with tip convection, which can be represented as a function of $L_c^{3/2} (h/kA_p)^{1/2}$ and r_{2c}/r_1 , is presented.

Regarding the calculation of the convective coefficient, is important to understand that various convective mechanisms may occur on the outer surface of the fins. In figure 5.5 a representative image of the final possible location of the LiDAR device (at the top of the car) and the linear velocity (V) due to the movement of the car and the rotation frequency (ω) correspondent to the rotation of the system are displayed.

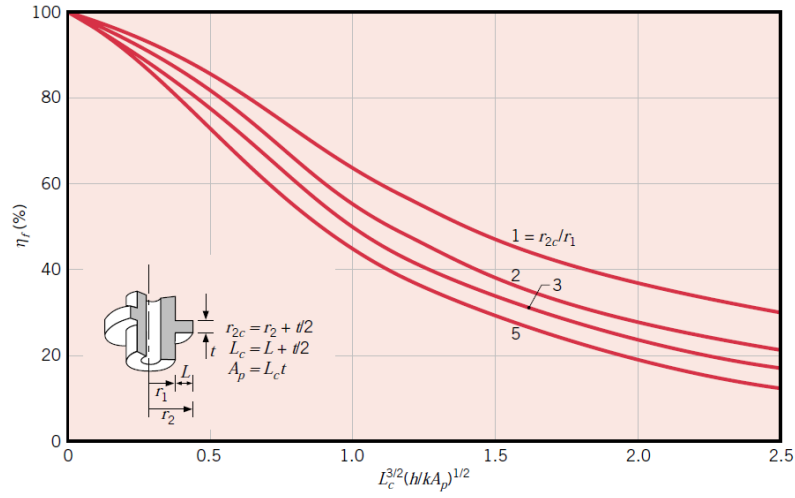


Figure 5.4: Efficiency of annular fins of rectangular profile [38].

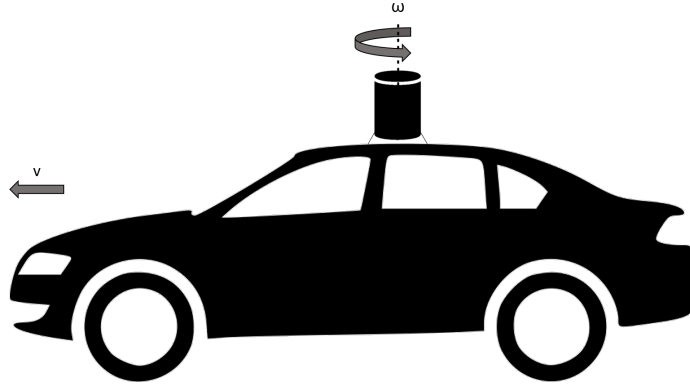


Figure 5.5: 2D Schematics of LiDAR sensor.

In this work, three convective effects on the exterior surface of the main chassis extended surfaces were considered:

- Natural convection around LiDAR;
- Forced convection due to linear movement of the car;
- Rotational movement due to rotation, which is also forced convection but during this work will be denominated as convection due to rotation due to nomenclature issues.

The estimation of the convective coefficient, and consequently the heat transfer, will depend on each of the previous movement. In the following subsections, it is presented correlations for each convective effect, including the calculation of the average Nusselt number $\overline{Nu}$, which consequently is used to calculate the average convective coefficient ($\bar{h}$) by the following equation:

$$\bar{h} = \overline{Nu} \frac{k}{D} \quad (5.5)$$

where,

k is the thermal conductivity (W/m.K) and D is the diameter (m).

5.2.1.1 Convective coefficient due to Natural convection

In the first approach for the calculation of the heat dissipation in the LiDAR sensor, it was considered that the car was stopped, the linear velocity is 0 m/s ($V=0$ m/s) and the LiDAR was not rotating ($\omega=0$ rad/s) as can be seen in figure 5.5. In other words, around the LiDAR it was assumed natural convection.

Natural convection occurs when there is no forced fluid motion. The convection currents are originated when a body force (due to gravitational field) acts on a fluid in which there are density gradients, which are commonly caused due to a temperature gradient. The net effect is a buoyancy force, which induces free convection currents [38]. In figure 5.6 the boundary layer around the external surface of a short vertical cylinder, due to natural convection is presented, which can be an approach of the LiDAR system.

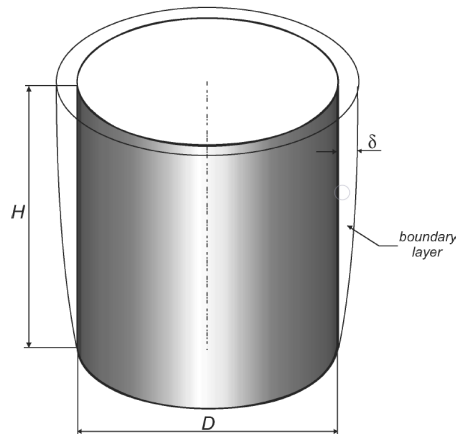


Figure 5.6: Free convection boundary layers on the lateral surface of short vertical cylinders [39].

For the calculation of the convective coefficient some dimensionless parameters numbers must be considered. First of all, the Grashof number (Gr_H), where the characteristic length is the height (H), which is a measure of the ratio of the buoyancy forces to the viscous forces acting on the fluid [38]:

$$Gr_H \equiv \frac{g\beta (T_s - T_\infty) H^3}{\nu^2} \quad (5.6)$$

where,

g Gravitational acceleration (m/s^2);

β Volumetric thermal expansion coefficient ($1/K$);

T_s Surface temperature ($^\circ C$);

ν Kinematic viscosity (m^2/s);

Then, the Rayleigh number (Ra_H) where the characteristic length is the height, which is product of the Grashof and Prandtl (Pr) numbers:

$$Ra_H = Gr_H Pr \quad (5.7)$$

According to [38] the correlations for the heat transfer in a vertical flat plate could be used for a vertical cylinder if the following condition is satisfied, meaning that the curvature effect can be neglected:

$$\frac{D}{H} \geq \frac{35}{Gr_H^{1/4}} \quad (5.8)$$

In this equation, D is the diameter of the cylinder and H is the height of the cylinder.

If the previous correlations are not satisfied, the curvature effect of the cylinder may not be neglected so, other correlations must be considered. In the table 5.1, it is possible to review some correlations for natural convection around vertical cylinders, which do not fulfill the previous condition (equation 5.8). The properties should be analysed at film temperature. These equations will be analysed later on.

Table 5.1: Correlation equations for vertical cylinders in natural convection.

Author	Range of Ra_H	Correlation equation
King [39]	$10^4 - 3,5 \times 10^7$	$\overline{Nu}_H = 0.55 Ra_H^{0.25}$
LeFevre and Ede [39]	—	$\overline{Nu}_H = \frac{4}{3} Ra_H^{0.25} \left[\frac{7Pr}{100+105Pr} \right]^{0.25} + \frac{4}{35} \frac{272+315Pr}{64+63Pr} \frac{H}{D}$
Kreith [40]	$10^5 - 10^9$	$\overline{Nu}_H = 0.555 (Ra_H)^{1/4}$

5.2.1.2 Convective coefficient due to forced convection

For these calculations, it was considered a linear velocity, not null, but a steady LiDAR ($V \neq 0$ m/s; $\omega = 0$ rad/s). According to literature, the LiDAR could be approached to an horizontal cylinder, where the Reynolds number (Re_D) characteristic length is the diameter (D) [38]:

$$Re_D = \frac{VD}{\nu} \quad (5.9)$$

Churchill and Bernstein [38] have proposed a single comprehensive equation that covers the entire range of Re_D for which data are available, as well as a wide range of Pr. The equation is

recommended for all $Re_D Pr \geq 0.2$, on which all properties are evaluated at the film temperature and has the form :

$$\overline{Nu}_D = 0.3 + \frac{0.62 Re_D^{1/2} Pr^{1/3}}{[1 + (0.4/Pr)^{2/3}]^{1/4}} \left[1 + \left(\frac{Re_D}{282,000} \right)^{5/8} \right]^{4/5} \quad (5.10)$$

Some other correlations such as Hilpert or Zukauskas were proposed but the Churchill and Bernstein equation is the most used as it is able to cover all range of Re_D .

5.2.1.3 Convective coefficient due to Rotation in Quiescent Air

In this approach, it was considered a steady car and a rotating LiDAR ($V = 0$ m/s; $\omega \neq 0$ rad/s).

Convective heat transfer from a horizontal rotating cylinder has been studied by many authors. First of all, it is important to define the rotational Reynolds number (Re_r) and the Grashof number (Gr_D) based on the diameter of the cylinder where properties are evaluated at film temperature.

$$Re_r = \frac{\omega D_o^2 \rho}{2\mu} \quad (5.11)$$

$$Gr_D \equiv \frac{g\beta (T_s - T_\infty) D^3}{\nu^2} \quad (5.12)$$

A summary of the literature correlations that can be used for rotating horizontal cylinders is presented in table 5.2.

Table 5.2: Convective heat transfer correlations from a horizontal rotating cylinder.

Author	Valid Criteria	Correlation equation
Anderson and Saunders [41]	$Re_r > Re_c = 1.09 Gr^{0.5}$	$\overline{Nu} = 0.1 Re_r^{0.66}$
Etemad [41]	$1000 < Re_r < 8000$	$\overline{Nu} = 0.11 [(0.5 Re_r^2 + Gr_D) \times Pr]^{0.35}$
	$8000 < Re_r < 65400$	$\overline{Nu} = 0.076 Re_r^{0.7}$
Dropkin and Carmi [41]	$0 < Re_r < 2500$	$\overline{Nu} = 0.095 [0.5 Re_r^2 + Gr_D]^{0.35}$
	$15000 < Re_r < 433000$	$\overline{Nu} = 0.073 Re_r^{0.7}$
Becker [41]	$800 < Re_r < 10^5$	$\overline{Nu} = 0.133 Re_r^{2/3} Pr^{1/3}$

5.2.1.4 Net heat transfer on the exterior surface

An estimation of the heat transfer was made on the outer surface of the main chassis.

As at this point of the work flow no information existed regarding the power dissipation of the heat sources of the system, it was decided to arbitrate a surface and initial temperatures in order to have an idea of the heat transfer dissipation through the system. So, the environment temperature was supposed to be 26°C and the surface temperature of the main chassis was assumed as 30°C.

In the table 5.3 some general parameters used to the calculations are presented, where H and D are exact values.

Table 5.3: Values used for heat transfer coefficient calculation.

Parameter	Value	Unit
H	76.15	mm
D	120	mm
T_s	30	°C
T_∞	26	°C

In the case of forced convection, it was assumed a linear velocity of 90 km/h and for the rotation of LiDAR a frequency of 10Hz was used.

It is important to notice that the correlation equations used in each case were the one which returned the smallest value for $\overline{Nu}$, in other words, the worst-case scenario, despite the results for each correlation not being that different from each other. After the calculation of the $\overline{Nu}$, $\bar{h}$ is calculated using equation 5.5.

The results concerning the forms of the convective effects on the outer surface of the LiDAR system are presented in table 5.4, along with the correlation used.

Table 5.4: Convective coefficient and heat transfer for each convective effect.

Convective effect	Correlation	h (W/m ² .K)	Q (W)
Natural convection	<i>King</i>	2.04	0.71
Rotation	<i>Dropkin and Carmi</i>	10.77	3.74
Forced convection	<i>Churchill-Bernstein</i>	39.16	12.87

The convective coefficient depends on the temperature of the surface and also the environment temperature mainly because the air properties depend on the film temperature. However, at this point of the work, there was no information regarding the amount of heat dissipated by each heat source, which will influence the surface temperature of the system. Even so, the dependency of temperature for the calculation of the convective coefficient is indirect so, the variation of the temperature does not change significantly the value for this coefficient, which will be verified later on.

The implementation of annular fins in the external surface of the aluminium chassis, significantly increase heat transfer by nearly 67%, once the area with fins is 0.088 m²(approx.) and the area without fins is 0.029 m² (approx.).

Comparing the 3 effects of convection, the one that stands is the one associated with the linear velocity of the car followed by the heat transfer associated with the rotation of LiDAR and last, the heat transfer associated with natural convection.

For an estimation of the heat dissipated by radiation, it was assumed the same temperatures and that the main chassis (subsection 4.2.1) behaves as a black body. The heat transfer obtained by radiation was 2,17 W (approximately).

5.2.2 Thermal bridges

Some thermal bridges were applied on the system. This thermal management solution was ensured mainly by two parts: the laser holder (subsection 4.2.2.1) and the laser spacer (subsection 4.2.2.2). At the same time, the laser holder was responsible for heat transfer through conduction radially from the FPGA component and the CoLID laser to the outer surface of the main chassis. In this way, the material of these parts is aluminium alloy essentially due to its high thermal conductivity.

The thermal bridges were applied to these components because at the time of the prototype development was already known that these two components had high power dissipation.

5.2.3 Insulation materials

As the previous mention in Chapter 4, electronic components will generate heat, unlike the optical elements. In this way, it was decided to insulate these two parts by the usage of materials with low thermal conductivity. For the fabrication of the optics chassis (subsection 4.2.3), which is in direct contact with the main chassis, the choice was a thermoplastic with high thermal resistivity.

Also, the implementation of a cork part, with very low thermal conductivity, approximately 0.034 W/mK [32], will guarantee almost perfect insulation between the optics and the main chassis.

5.2.4 Fans

When it comes to the selection of the fan, the most important parameters and requirements which were taken into account are:

- **Size:** should be small enough to fit on the PCB chassis (section 4.2.2), being the fan thickness the most critical dimension as it must be below 3mm;
- **Power consumption:** should be low to not overload the system;
- **Cost:** should be as low as possible as the purpose is to build a low-cost LiDAR;
- **Operating voltage:** to avoid the usage of converters should be 3, 3.3, 5 or 12V;
- **Operating temperature:** should fulfil the automotive standards, it is, operating between -40 to 85°C;
- **Air flow:** As at this point of the work the total heat dissipation was not yet defined, no calculations were possible to estimate the necessary airflow for the system.

After a market research bearing in mind all the previous requirements, *UF3F3-500 Sunon* mini Fan seemed to fulfil almost all the specifications except the operating temperature. The most important specifications are shown in the table 5.5 and in the appendix B the datasheet of the product is presented.

Table 5.5: UF3F3-500 Sunon mini Fan main specifications.

Parameter	Value
Size (mm)	15x15x3
Rated power (W)	0.1
Cost (\$/unit)	18.21
Rated Voltage (VDC)	3
Operating temperature (°C)	-40 to 70
Air flow (l/min)	8.75

It was decided to implement three fans and glue them to the PCB chassis (section 4.2.2). The adhesive chosen is a general-use Epoxy, however, when it comes to a commercial LiDAR system another approach for fastening should be adopted to be possible to assemble and disassemble easily.

Regarding the location, one of them is placed on the centre of one of the PCB holder (sub-section 4.2.2) and the other two are located on the other part of the PCB holder, at 25° above the x-axis, as it is shown in figure 5.7a. For the vertical layout was decided to have the 3 fans at different heights to allow that the fan's airflow reaches all board components (figure 5.7b).

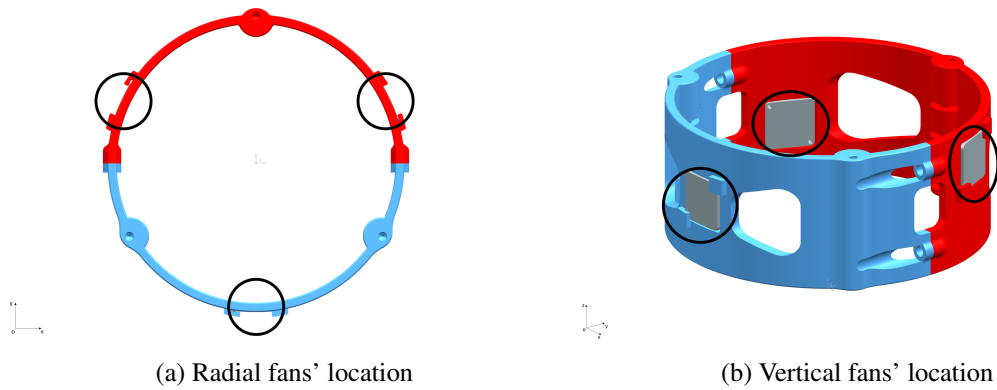


Figure 5.7: Mini fans location.

5.3 Components temperature monitoring

The electronic components will generate heat which will increase the temperature inside the housing. So, it was decided to monitor experimentally the temperature of the electronic components during their operation and power consumption. These experimental tests will be important for the numerical simulations (section 5.4).

The ideal scenario was to monitor all the components of each PCB and also the CoLID laser, however most of the boards were not yet defined so, for at this stage, it was only possible to measure the temperature and the power consumption of the laser and the TE0820-03 board.

5.3.1 TE0820-03 Board

TE0820-03 board is connected to the carrier board and has the laser on the top of it, according to figure 3.3. According to the manufacturer (*Trenz electronic*) the operating temperature should be between -45°C and 85°C .

For the temperature monitoring of this board was used a Digital Bench multimeter with one thermocouple (T01), a supply of 3,3V was set (according to the component datasheet) and also a thermal camera for the temperature distribution on the PCB. The setup is present in figure 5.8.

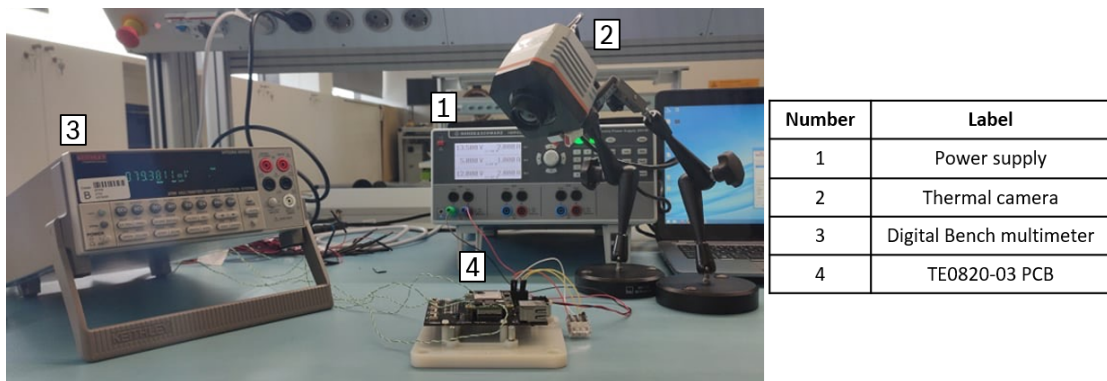


Figure 5.8: Setup for TE-0820 Board temperature monitoring.

Among its various components, the most critical is the FPGA (Field-programmable gate array) as it has the highest power consumption when comparing to the other components of this board. So the thermocouple (T01) is placed on the top of this component, according to figure 5.9.

In figure 5.10 the temperature of the component during the operation is represented, revealing that after around 25 min the temperature was stabilized at around 80°C .

During the test the power consumption was around 3,6 W (current was 1,1 A) and the environment temperature (room temperature) was constant and equal to 26°C .

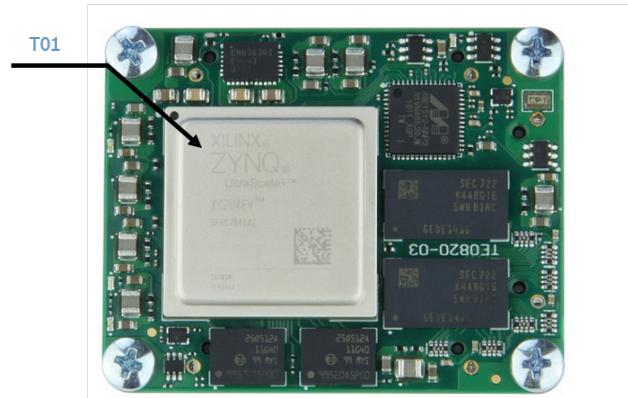


Figure 5.9: Location of the thermocouple on TE0820-03 Board.

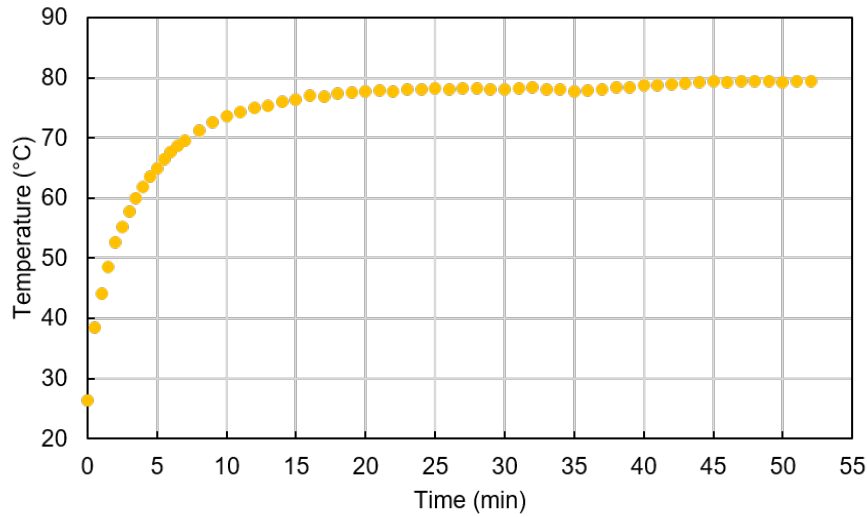


Figure 5.10: FPGA Temperature monitoring.

5.3.2 Laser Source

According to the manufacturer, the CoLID laser can work in the temperature range of -35 to $+75$ °C. Such a wide range of temperature will bring a large change in output power however if the change in temperature is small the laser can achieve a stable output.

In this way, tests were performed to evaluate the temperature during the time while operating the laser. The laser was supported by a heat sink and under this, there was a fan which could be turned on/off (figure 5.11). To study the power output influence on the temperature, the voltage was set for 500mV or 1000mV to control the output power. So, for each voltage, tests were performed with the fan turned on and with no fan usage.

Pulse width ¹ and repetition rate ² were kept constant and the values were 10ns and 313 kHz respectively. For measuring the temperature a Digital Bench Multimeter was used with 4 ther-

¹A measure of the time between the beginning and end of the pulse, in other words, the duration of the pulse.

²The frequency at which pulses are emitted.

thermocouples named as T101, T102, T103 and T104 which were placed around the laser (T101 and T102) and at the top and bottom (T103 and T104 respectively) as well as an Optical trap capable of absorbing 5W power and two outputs, as it is presented in figure 5.11. For the supply voltage, according to the datasheet, it was set for 12V.

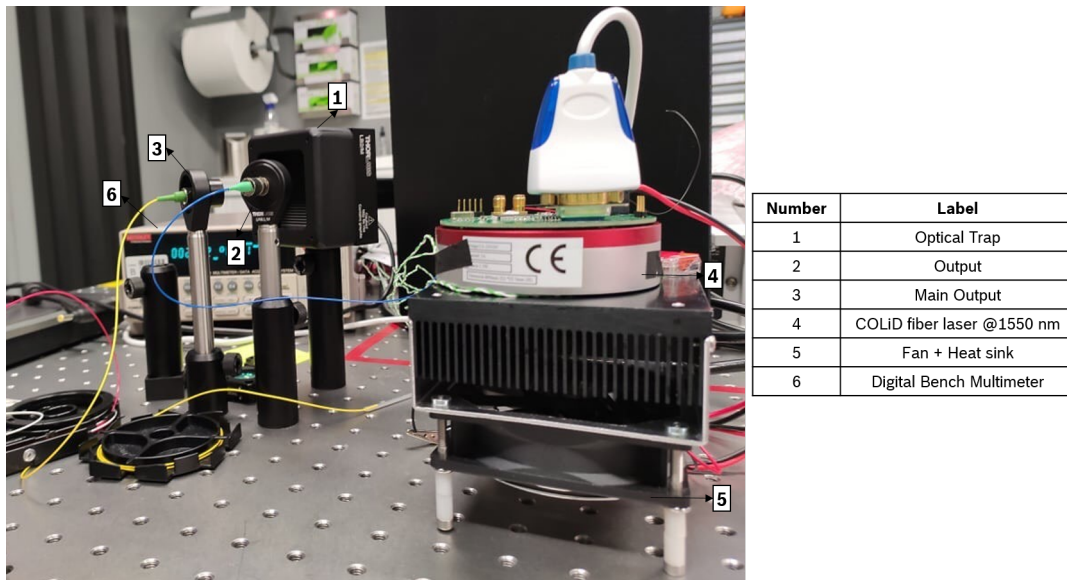


Figure 5.11: Setup.

In the following graphic (figure 5.12) the variation of temperature with time considering the average temperature measured in the three thermocouples (T101, T102 and T103) is presented. T104 thermocouple was in contact with the heat sink so is not considered.

As it is possible to notice, higher temperatures are presented when the voltage is set for 1000mV and no fan is used. It is important to take into account that there is a quicker temperature stabilization when fans are turned on for both 1000mV and 500mV.

During cooling the same happens, in other words, cooling is faster when fans are turned on and takes longer for cooling when the voltage is set for 1000mV and no fan is used.

For this LiDAR application, the power output is set for 1000mv which allows higher range, the repetition rate is 313KHz and pulse width of 10ns.

In figures 5.13 are presented the graphics for the temperature monitoring of CoLiD laser when it is operating (figure 5.13a) and when is not operating, which means, the laser is turned off (figure 5.13b) both with no fan usage.

For this power output, it is important to remark that the tests were performed at an environment temperature (room temperature) of 26°C and the power supply was around 16W.

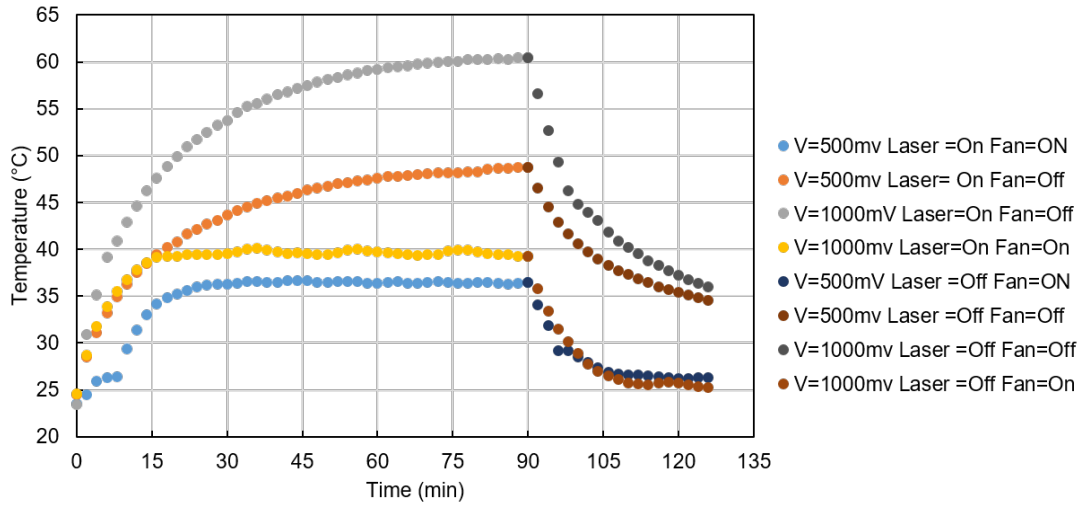
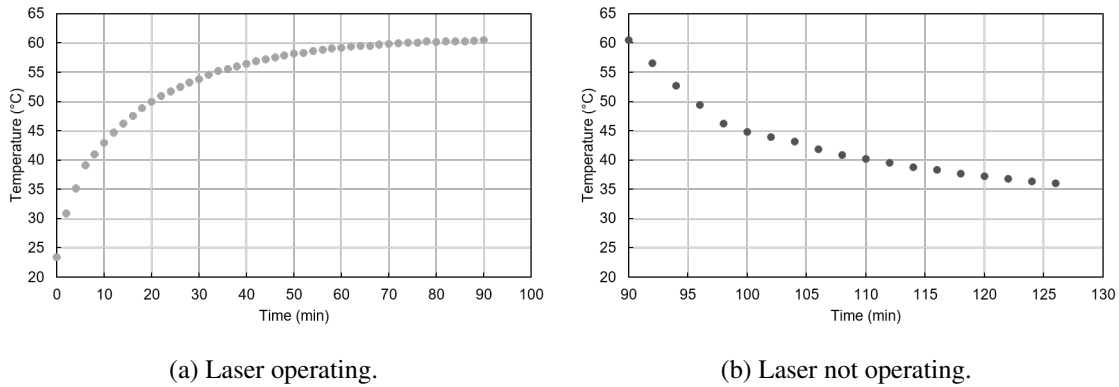


Figure 5.12: Temperature with time for CoLID laser.



(a) Laser operating.

(b) Laser not operating.

Figure 5.13: Temperature with time for the 1000mV without fan.

5.4 Numerical simulation

The analysis regarding the thermal status was made for the housing prototype using FLoEFD software [42], based on a computational fluid dynamics (CFD) analysis solution. The simulation properties were as follows:

- **Geometry:** was simplified (no wires and no round edges) and it was only considered the Data handling and Advanced processing subsystems and assumed that the contact resistance on the top of this systems was infinite.
- **Component Materials:** The materials selected for each component are:
 - PCBs: material assumed to be a general PCB with 4 layers (named Fr-4);
 - Exterior chassis, PCB holder, Laser holder, Laser spacer and Bottom case: Aluminium alloy;
 - Screws: Stainless steel;
 - MAR2100 case: LQFP (low-profile quad flat) package;

- CoLID case: Aluminium alloy;
- FPGA: IC (Integrated circuit) package;
- Fans: Liquid-crystalline polymer (LCP);
- Connectors: Typical connector.

In table 5.6 the properties for each material used for this simulation are presented: Density (ρ), Specific heat (c_p) and Thermal conductivity (k).

Table 5.6: Materials defined for the thermal simulation.

Material	ρ (kg/m ³)	c_p (J/kg-k)	k (W/m-k)
Aluminum alloy [42]	2689	902	237
Stainless Steel [42]	8100	510	15,1
LCP [30]	1400	1020	0,2
PCB 4 layers [42]	2145	1136	Axial 0,25 Radial 16,25
Typical connector [42]	2000	400	x,y axis: 5 z axis: 20
LQFP package [42]	2000	490	0,3

• **Assumptions:**

- Steady-state condition;
- Rotation of 10Hz;
- Air considered as incompressible ideal gas;
- Negligible radiation exchange with surroundings.

• **Boundary Conditions:**

- Infinite contact resistance on the top face of the main chassis, where it was supposed to fix the optics chassis;
- $T_\infty = 26^\circ\text{C}$;
- Heat sources: FPGA, CoLID laser and MAR2100;
- Fans: performance curve was considered (Appendix B).

5.4.1 Heat sources

For the determination of the power dissipation on each heat source, first it is necessary to measure the voltage applied (V) and the electric current (I) at the entrance of the electronic device under full-load conditions and to apply them into the relation [27]:

$$W_e = VI = I^2 R \quad (5.13)$$

where,

W_e is the electric power consumption of the electronic device, this is, the input power.

According to the first law of thermodynamics, the energy input into a system is equal to the energy output from the system. Considering that the only form of energy leaving the electronic device is heat generated (Q) as the current flows through resistive elements, it is possible to conclude that the heat dissipation of an electronic device is equal to its power consumption ($Q = W_e$).

There are exceptions to this general rule, this is, equipment that outputs other forms of energy as well, such as the emitter tubes of radar, radio, or TV installation emitting radiofrequency (RF) electromagnetic radiation. In such cases, the heat dissipation will be equal to the difference between the power consumption and the RF power emission [27].

In matters of simulation, the first approach made for all the heat sources was to assume that the power consumption was equal to power dissipation and was made an individual simulation for each heat source, considering the initial temperature of 26°C.

In the case of the μ mirror board, the simplified model kept only the MAR2100 component and the PCB board (μ mirror controller board), defining the power dissipation equal to the power consumption, this is, 0,5 W. This power consumption was defined on the component datasheet and the obtained global component average temperature by simulation was equal to 45,6°C. The experimental temperature was not possible to be obtained for comparison.

The figure 5.14 shows the distribution of temperature on the simplified μ mirror board.

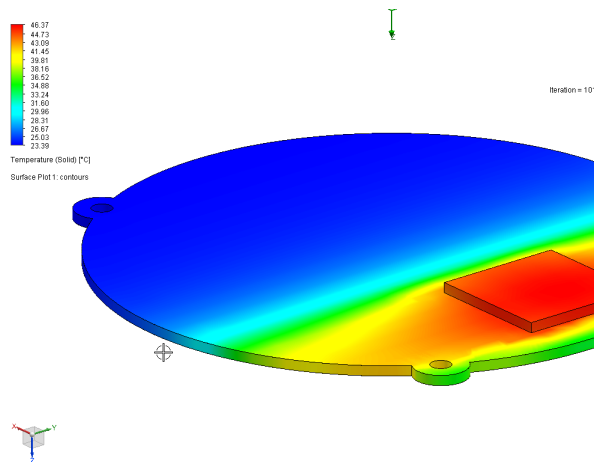


Figure 5.14: Temperature distribution on the simplified μ mirror controller board with MAR2100 component.

For the CoLID laser, it is not correct to assume that the power consumption is equal to the power dissipation as other forms of energy should be considered: radiation for example. So, in this case, as the laser's surface temperature was previously monitored, some iterations were made to estimate the power dissipation, in other words, some simulations were performed in order to obtain the power dissipation that equals the temperature obtained experimentally (subsection 5.3.2). So, the power dissipation obtained was 6W and the final global average temperature was 74,0 °C (around 19% higher than the experimental maximum temperature). It is important to notice that the laser was simplified achieving an homogeneous aluminium solid with the same exterior dimensions of the case and the same weight.

Figure 5.15 shows the distribution of temperature on the simplified CoLID, corresponding to a 6W power dissipation.

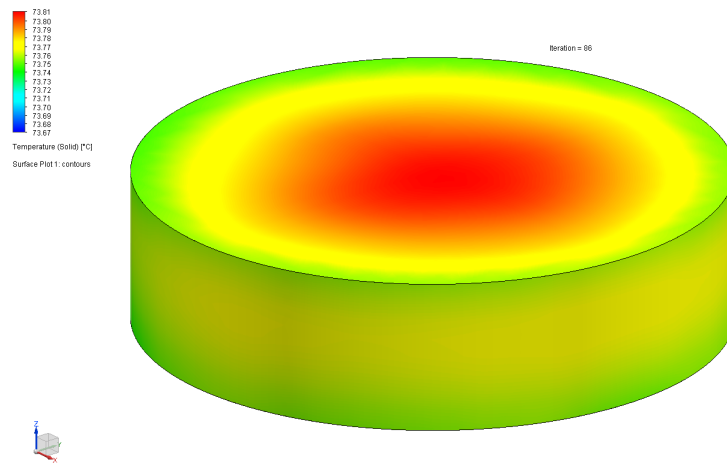


Figure 5.15: Temperature distribution on the simplified CoLID laser.

The TE0820-03 Board was simplified keeping only the PCB board and the FPGA component. In the first simulation, where the power consumption was equal to the power dissipation, the obtained temperature was 125,6°C, which was very different from the maximum experimental temperature (subsection 5.3.1).

As the power input was for supplying all the components on the board and not only the FPGA, the power losses could be related to the consumption of these components, not considered for these simulations. So, some iterations were performed to obtain the power dissipation that equals the temperature obtained experimentally. In this way, the obtained average global component temperature was 87°C (around 8% higher than the experimental maximum temperature) and corresponds to 2W of power dissipation.

Figure 5.16 displays the temperature distribution on the simplified TE0208 board, for a power dissipation of 2W.

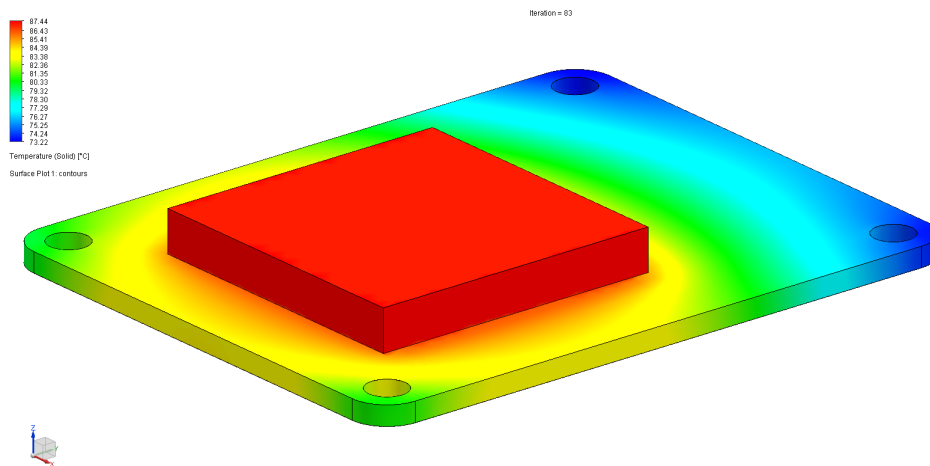


Figure 5.16: Temperature distribution on the simplified TE0208 board.

In table 5.7 presents the power consumption and the assumed power dissipation for each heat source, for an initial environment temperature of 26°C.

Table 5.7: Heat sources power consumption and power dissipation.

	Voltage (V)	Current (A)	Power consumption (W)	Power dissipation (W)
FPGA	3.3	1.1	3.6	2.0
CoLID	12.0	1.3	16.0	6.0
MAR2100	3.3	0.2	0.5	0.5

After knowing the power dissipation by each component, it is possible to perform simulations on the global model varying some parameters, which will be presented on the next subsections.

5.4.2 Initial temperature variation

In the first simulation, there were chosen different initial temperatures. It was chosen to first simulate for an environment temperature of 26°C and then for the extreme temperatures of the automotive standards: -40 and 85°C.

The temperature distribution for each initial temperature (T_i) are presented in the following figures: for $T_i=26^\circ\text{C}$ in figure 5.17, for $T_i=85^\circ\text{C}$ in figure 5.18 and for $T_i=-40^\circ\text{C}$ in figure 5.19. It is important to remark that the colours scales are different for each initial temperature.

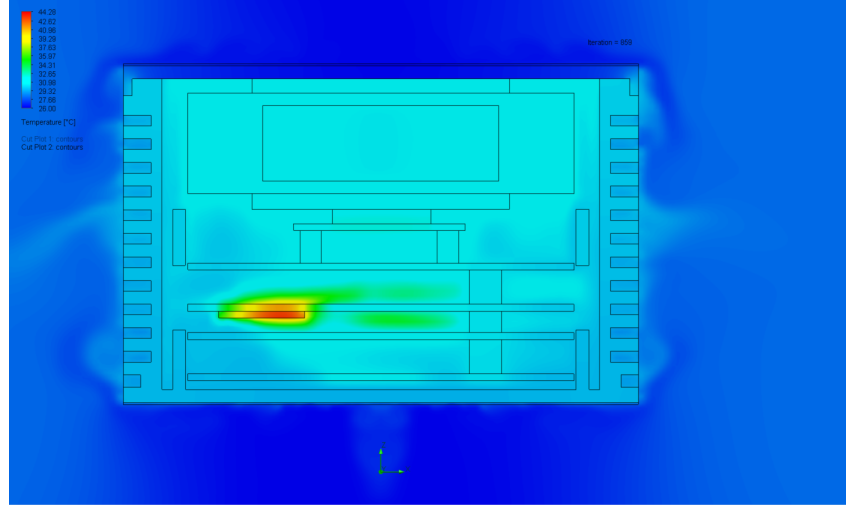


Figure 5.17: Temperature distribution for the $T_i=26^\circ\text{C}$.

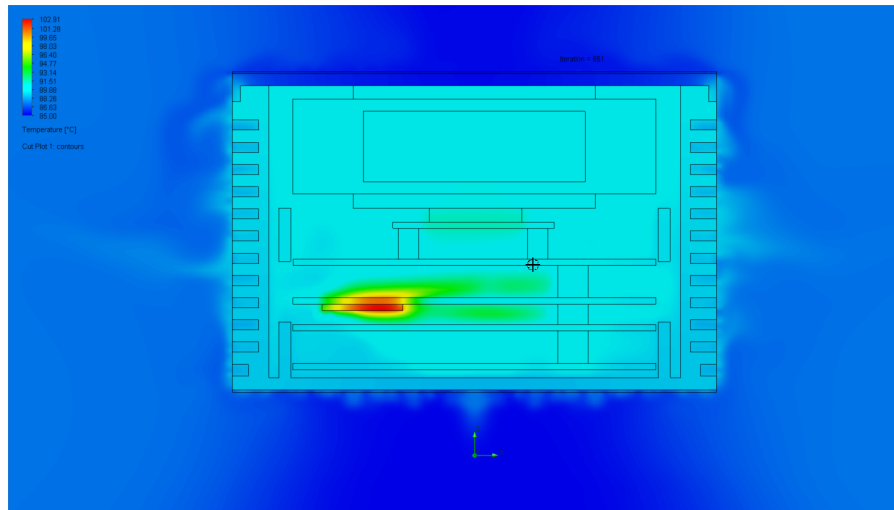


Figure 5.18: Temperature distribution for the $T_i=85^\circ\text{C}$.

In table 5.8 the average global temperature for each heat source according to the initial temperature are presented where,

T_M MAR2100 global component average temperature ($^\circ\text{C}$)

T_F FPGA global component average temperature ($^\circ\text{C}$)

T_C CoLID global component average temperature ($^\circ\text{C}$)

For all initial temperature, the critical component was always the MAR2100 because its package is plastic and no thermal bridge was applied to this component. On the other hand, the laser was assumed to be highly thermal conductive (aluminium) as well as the FPGA package, having low thermal resistivity.

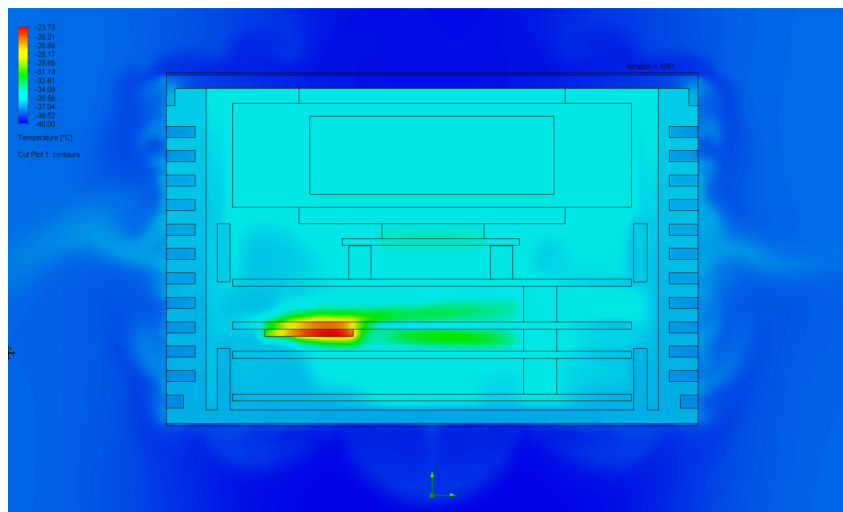


Figure 5.19: Temperature distribution for the $T_i=-40^\circ\text{C}$.

Table 5.8: Heat source average temperature for each initial temperature.

T_i ($^\circ\text{C}$)	-40	26	85
T_M ($^\circ\text{C}$)	-26,87	40,73	103,75
T_F ($^\circ\text{C}$)	-34,70	31,80	91,05
T_C ($^\circ\text{C}$)	-35,39	31,07	90,32

According to the datasheet of the components, the maximum temperature allowed for the FPGA [43] and the MAR2100 [44] is 85°C and the minimum operating temperature is -40°C . For the CoLID laser, the maximum operating temperature is 75°C and the minimum operating temperature is -35°C .

So, when the initial temperature is 85°C , the temperature on all the heat sources exceeds the operating condition so the system will not work properly. Therefore, by iterations, it was defined that the maximum operating temperature of the system is 70°C . In the table 5.9 the average global temperature for each heat source when the initial temperature is 70°C is presented, where the components do not exceed their maximum operating temperature.

Table 5.9: Heat source average temperature for the initial ambient temperature of 70°C .

	$T_i=70$	Max. Oper. Temp.
T_M ($^\circ\text{C}$)	84,99	85
T_F ($^\circ\text{C}$)	75,87	85
T_C ($^\circ\text{C}$)	75,14	75

5.4.3 Heat transfer mechanisms

Inside the housing and in each heat source, it is important to understand the heat transfer mechanisms associated with each component, when the radiation heat transfer is not taken into consideration.

For the laser source, it will be in direct contact with the laser holder (subsubsection 4.2.2.1) and with the laser spacer (subsubsection 4.2.2.1). As these parts are highly thermally conductive, the heat will be dissipated by conduction on the top and bottom faces, whereas on the side area of this component there will be heat dissipation by convection. The heat transfer on the laser source is presented in figure 5.20.

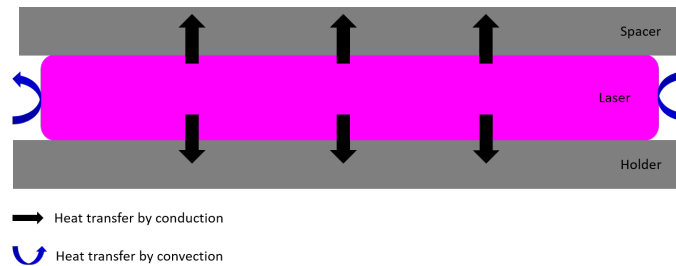


Figure 5.20: Heat transfer mechanics on the laser source.

The FPGA component will be linked to the PCB board spreading heat by conduction with it. On its top, it will have a small film of thermal paste however in terms of simulation, it is assumed that the FPGA is in contact with the laser holder (subsubsection 4.2.2.1). The FPGA side faces will transfer heat by convection. The figure 5.21 illustrates the heat transfer on the FPGA.

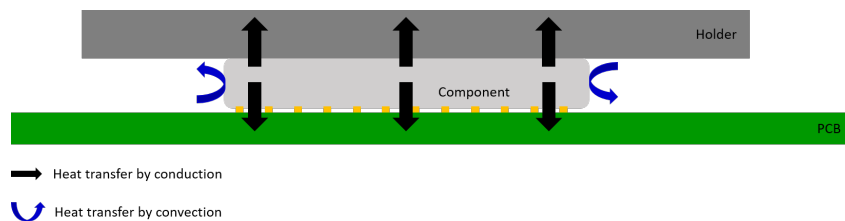


Figure 5.21: Heat transfer mechanics on the FPGA.

As regards the MAR2100, the heat transfer occurs mainly by convection as conduction only happens on one of its faces, where will exchange heat with the PCB board. Figure 5.22 illustrates the heat transfer mechanisms on the component.

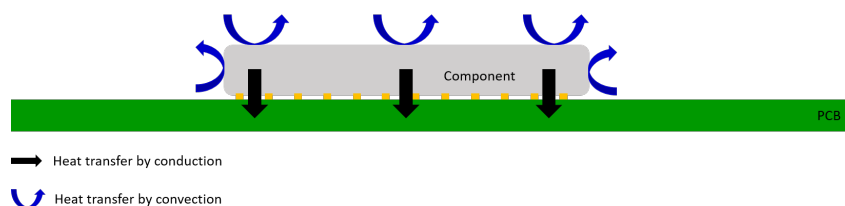


Figure 5.22: Heat transfer mechanics on the MAR2100.

Table 5.10 presents the numerical values for each heat transfer mechanism for each heat source component where,

Q_{conv} is the heat transfer by convection;

Q_{cond} is the heat transfer by conduction;

Q is the total heat dissipation.

Table 5.10: Heat transfer on the heat sources.

	Mar2100	FPGA	CoLID
Q_{conv} (W)	0,14	$\approx 0,00$	0,19
Q_{cond} (W)	0,36	2,00	5,78
Q (W)	0,50	2,00	5,97

So, the numerical simulation is according to what was expected, which means:

- On the MAR2100, 72% of the total heat of the component is dissipated by conduction, whereas 28% is dissipated by convection. Despite the convective surface area is greater than the conductive surface area, the PCB board has smaller thermal resistance than the air;
- On the FPGA the convection effects are almost negligible once the convective area is much smaller than the conductive surface area and also the laser holder part and the PCB board have higher thermal coefficient;
- For the laser source, only nearly 3,4% of the heat is dissipated by convection on the side area of the component. The remaining 96,6% is dissipated by conduction through the laser holder and the laser spacer.

5.4.4 Fans performance

The fans performance were evaluated by numerical simulation at the initial temperature of 26°C. In table 5.11 displays some relevant temperature values for the system with and without fans and even the variation of these values.

Table 5.11: Temperatures for the system with and without fans.

	No Fans	Fans	Δ (%)
T_{airi} (°C)	31,01	30,62	1,28
T_M (°C)	42,86	40,73	5,23
T_F (°C)	31,91	31,80	0,36
T_C (°C)	31,17	31,07	0,33

Where;

T_{airi} is the average fluid temperature inside the rotating system.

As it is displayed, the usage of the fans does not bring a relevant temperature decrease in the global system once the average temperature inside the housing only decreases approximately 1,28%. The global average temperature on MAR2100 decreases the highest value (approximately 5,23%), once it has around 28% of heat transfer by convection, the highest percentage when compared to the other components.

In this way, as future work, the fans should have better airflow to increase their performance and lower the inside temperature of the system.

5.4.5 Rotational effects

For studying the effects of the forced convection due to rotation, the initial temperature was defined as 26°C. Figure 5.23 presents the temperature distribution on the simplified model. When comparing to the temperature distribution for the same conditions but considering the rotating system in figure 5.17, the global temperature is much higher.

A comparison between the temperatures obtained for the system with natural convection (no rotation) around the system and the system with forced convection (rotation) is made. The temperatures are presented in table 5.12 for the rotational and non-rotational systems.

It is possible to notice that the forced convection decreases the temperatures of the heat sources by nearly 50% as well as the inside air temperature. This phenomena truly enhances the heat transfer rate.

5.4.5.1 Analytic and numerical results

The comparison of the analytic expressions with the values obtained via simulations is very important to understand the reliability of the results. So, table 5.13 presents the surface temperature,

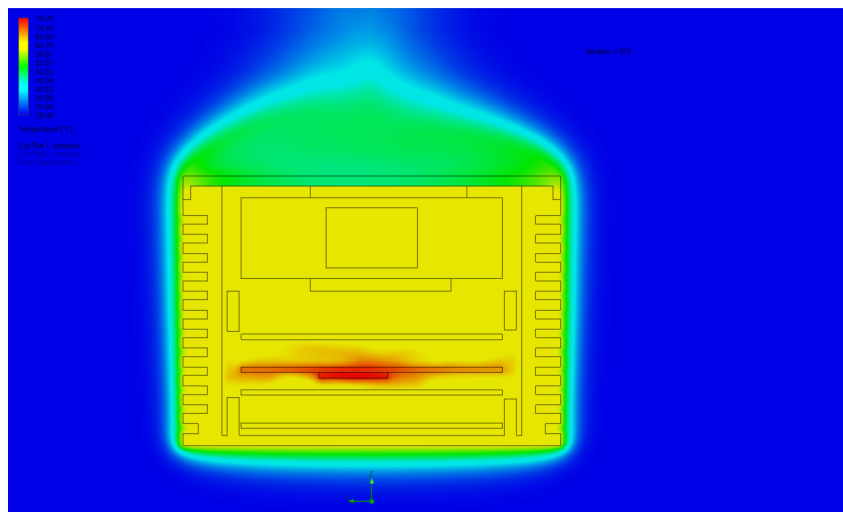


Figure 5.23: Temperature distribution for the system with no rotation.

Table 5.12: Temperatures for the system with and without fans.

	No rotation	Rotation	Δ (%)
T_{airi} (°C)	64,87	30,62	52,80
T_M (°C)	76,81	40,73	46,97
T_F (°C)	66,05	31,80	51,86
T_C (°C)	65,32	31,07	52,44

obtained by numerical simulation, for a rotational and a non-rotational system, when considering an initial temperature of 26°C.

Table 5.13: Surface temperature by numerical simulation for rotational and non-rotational system.

	T_s (°C)	T_i (°C)
Rotating	30,62	26
No rotation	64,87	

Using the correlation mentioned on the subsubsection 5.2.1.3 for the convection due to rotation, the correlations for natural convection (subsubsection 5.2.1.1) and the temperature values of the table 5.13, it was possible to calculate the convective coefficient and the heat transfer rate, presented in table 5.14.

Table 5.14: Analytic calculations considering the numerical temperatures for the rotational and non-rotational systems.

	Convective coefficient($\text{W/m}^2 \cdot \text{K}$)	Heat transfer rate (W)
Natural convection	3,36	11,5
Rotation	10,75	3,65

When considering the estimations for the convective coefficient presented in table 5.4 for the natural convection and the forced convection due to rotation, the convective coefficients are similar.

When considering the natural convection the convective coefficient for the numerical simulation is around 39% higher when comparing with the coefficient obtained by analytic calculations. This occurs due to the temperature variation which was considered: for the initial estimation the surface temperature was considered as 30°C and in the numeric simulation the obtained temperature was $64,87^\circ\text{C}$, causing that difference on the convective coefficients.

For the forced convection due to rotation, the estimated surface temperature (30°C) was almost the same as the one obtained by numerical simulation ($30,62^\circ\text{C}$), the reason why the convective coefficients are approximately the same.

Chapter 6

Functional prototype

Chapter 4 dealt with the CAD project development along with the desired manufacturing processes and materials for each designed part.

For the machined components, a 2D drawing was elaborated, which implied the calculation of the tolerances to ensure the assembly of all parts and due to the manufacturing process limitations, some parts had to be adjusted to accommodate said limitations. The final 2D drawings of each part are given in appendix A.

6.1 Parts manufacturing

The designed parts along with the 2D drawings were sent to the manufacturer to produce the prototype.

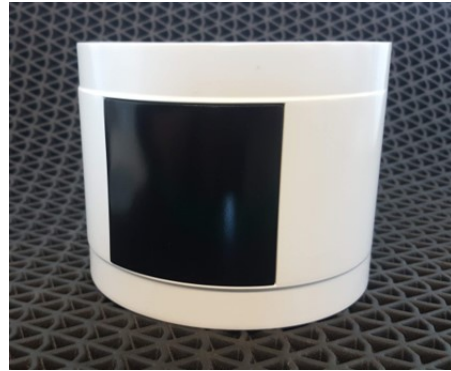
The optics chassis and the support part [28] were fabricated using the stereolithography (SLA) process once parts can be created with extremely high quality, with finely detailed features and complex geometrical shapes. For these parts, the minimum layer thickness, this is, the resolution used on the manufacturing process was 0.15 mm. The post-processing for these parts includes shot blasting and then painting (white or black). Figures 6.1a and 6.1b present the SLA manufactured parts.

For some of the aluminium alloy parts (bottom holder, laser holder and spacer, optic holder and top holder) were fabricated using CNC machining. Additive manufacturing (AM) could be an option however the biggest difference when comparing AM of metal to plastic is the precision and accuracy of process control and part quality controls that must be implemented to ensure strict adherence to design requirements. The parts were used as machined, not adding costs. In figures 6.2a, 6.2b, 6.3b, 6.3a and 6.4 the CNC machined components are displayed.

In more complex parts, such as the PCB holder and the main chassis, CNC machining was combined with wire Electrical Discharge Machining (EDM) which allows the production of complex shapes with good accuracy. It is important to notice that the main chassis was cropped in 100° to be possible to see the components inside the prototype. The figures 6.5a, 6.5b and 6.6 show the manufactured parts by CNC machining and wire EDM.



(a) Support.



(b) Optic chassis.

Figure 6.1: SLA fabricated parts.



(a) Bottom holder.

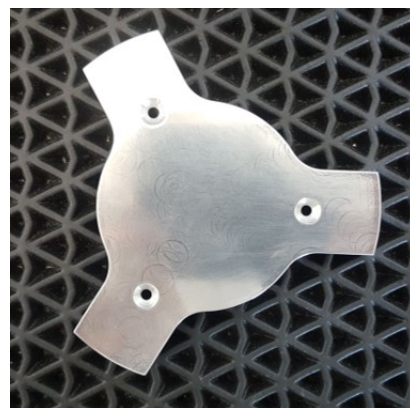


(b) Top holder.

Figure 6.2: Top and bottom holders: CNC machined parts.



(a) Laser holder.



(b) Laser spacer.

Figure 6.3: Laser holder and spacer: CNC machined parts.

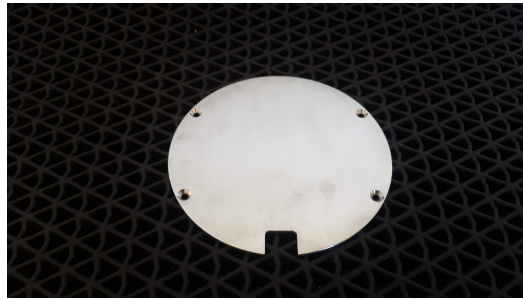
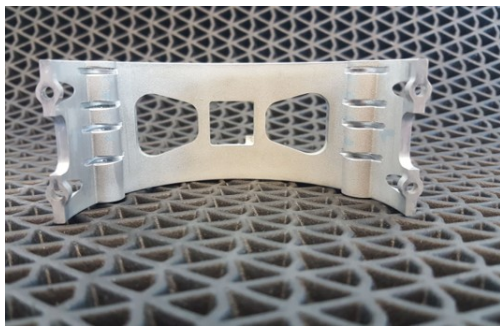
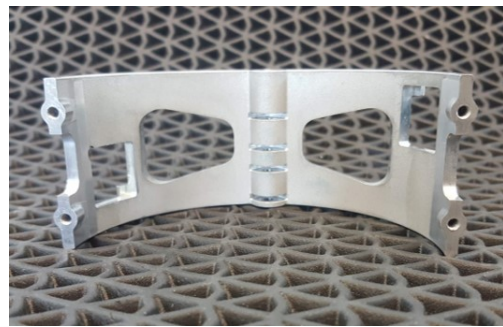


Figure 6.4: Optic holder: CNC machined part.



(a)



(b)

Figure 6.5: PCB holder: Combined CNC machined and wire EDM .

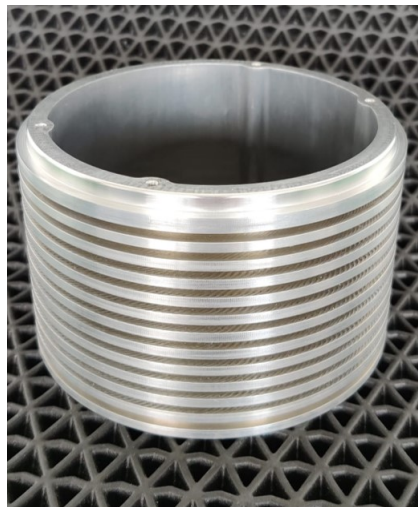


Figure 6.6: Main chassis: Combined CNC machined and wire EDM

The PCBs board were fabricated without the components just to have an idea of the boards position. The material used is FR-4 ¹ and were cut using CNC (milled). Figure 6.7 presents the four boards used for the prototype.

¹FR-4 is glass-reinforced epoxy laminate material.

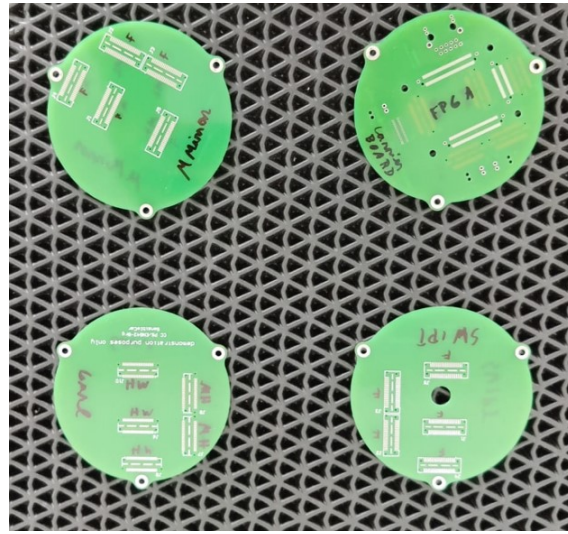


Figure 6.7: PCB board used in the prototype.

For this prototype cork part was cut from a cork sheet. Figure presents 6.8 the cork part is present. It is possible to notice that the part thickness could be increased to make the component more robust.

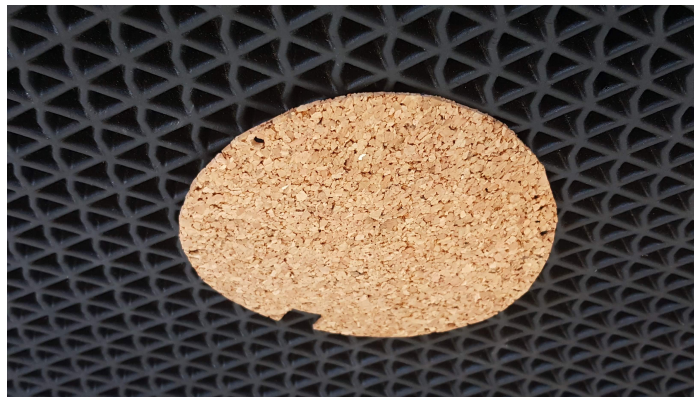


Figure 6.8: Cork part.

In the table 6.1 a summary of the manufacturing details of each designed part are presented.

The machined parts fulfilled all the tolerances imposed in the 2D drawings sent to the manufacturer. Relatively to the printed parts, also achieved the imposed tolerances, ensuring that all the parts fit in.

The standard parts such as the CoLID laser, the *Sunon* fans, the bearing as well as the screws and inserts were ordered. In table 6.2 the standard components used to build up the prototype are displayed.

Table 6.1: Manufactured parts details.

Component	Manufacturing process(es)	Material	Surface finishing
Bottom holder	CNC machining	Aluminium alloy	Not applied
Cork part	-	Cork	Not applied
Laser holder	CNC machining	Aluminium alloy	Not applied
Laser spacer	CNC machining	Aluminium alloy	Not applied
Main chassis	Wire EDM CNC machining	Aluminium alloy	Not applied
PCB boards (x4)	CNC machining	FR-4	Not applied
PCB holder	Wire EDM CNC machining	Aluminium alloy	Not applied
Optic holder	CNC machining	Aluminium alloy	Not applied
Optic chassis	SLA	<i>Accura 25</i>	Shot blasting Painting
Support [28]	SLA	<i>Accura 25</i>	Shot blasting Painting
Top holder	CNC machining	Aluminium alloy	Not applied

Table 6.2: Standard parts.

Component	Quantity
CoLID laser	1
<i>Sunon</i> fans	3
Bearing SKF W 6300-2RS	2
Screws	31
Inserts	7

6.2 Assembly sequence

The next subsections present the assembly sequence which was followed to mount the prototype. It is important to notice that in some cases there are other mounting possibilities.

6.2.1 Fans assembly

Using an epoxy adhesive, the fans were glued on the specific extended areas (figure 6.9b). In figure 6.9 the fan bonded to one of the parts of the PCB holder is presented. In the other half of the PCB holder, the two fans were also bonded, as it is displayed in figure 6.10.

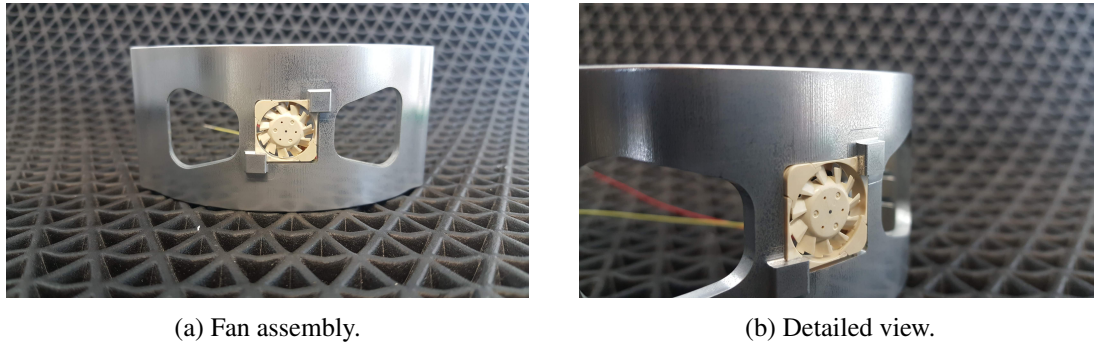


Figure 6.9: Fan assembly on one of the two parts of the PCB holder.

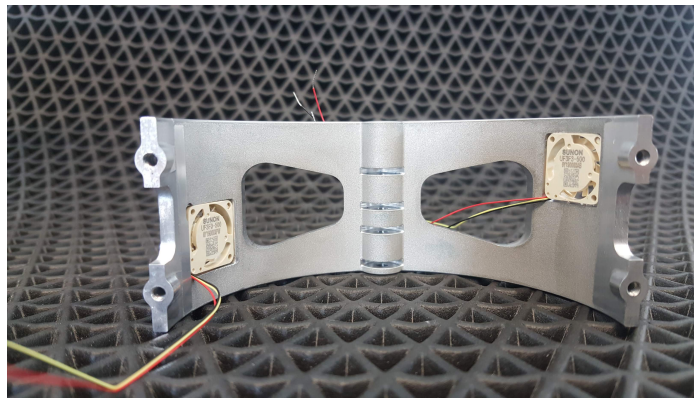


Figure 6.10: Fan assembly on the second half of the PCB holder.

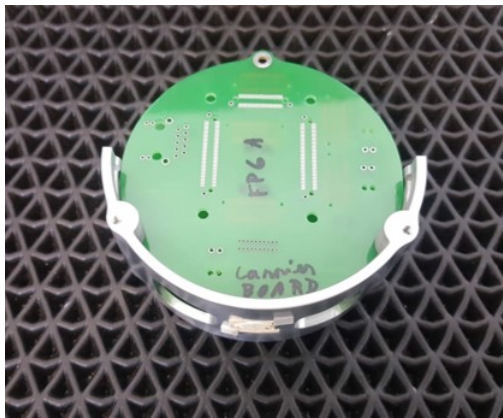
During the 2D drawings for these two parts there was a special attention to the tolerances referred on the fans datasheet for the frame dimensions.

6.2.2 PCBs assembly

The boards were firstly fitted on the PCB holder which has two slots for the PCBs ears. In figure 6.11 the first step for the PCB assembly is displayed.

Afterwards, the other half of the PCB holder was fitted on the other ear of the boards and the two parts of the PCB holder were fastened using four screws, as it is displayed on figure 6.12.

The slots on the PCB holder took into account the tolerances associated with the boards.

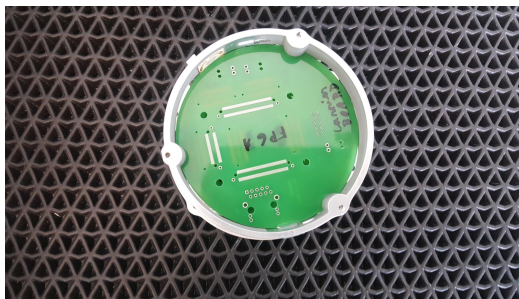


(a) Top view.

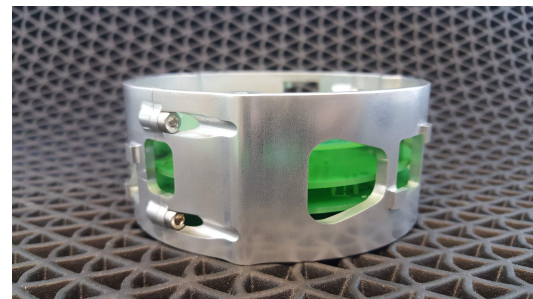


(b) Front view.

Figure 6.11: PCB assembly on one of the two parts of the PCB holder.



(a) Top view.



(b) Front view.

Figure 6.12: PCB holder assembly.

6.2.3 Bottom holder assembly

The bottom holder, already with the bearing coupled on the shaft of this component, was fastened on the PCB holder, using three screws passing through the boards' ears and threaded on the PCB holder.



Figure 6.13: Bottom holder assembly.

6.2.4 Laser assembly

Initially, the laser is fastened to the laser holder part using three screws, as it is displayed in figure 6.14.

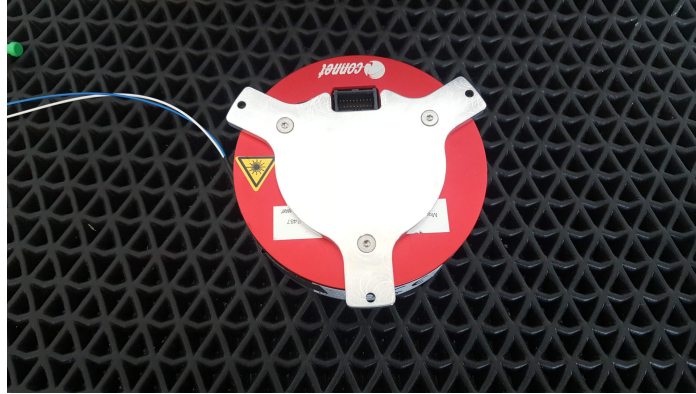


Figure 6.14: Laser holder assembly.

Afterwards, the laser and laser spacer set is fastened to the PCB holder using three screws, as it is shown in figure 6.15.

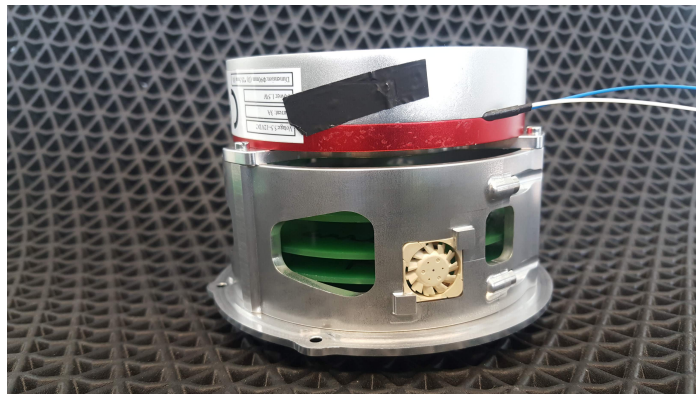


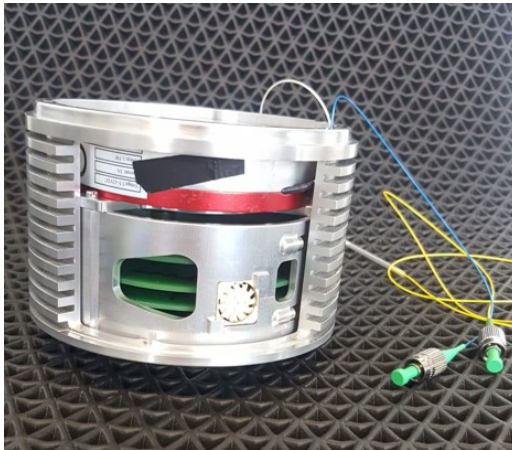
Figure 6.15: Laser holder assembly on the PCB holder.

6.2.5 Main chassis assembly

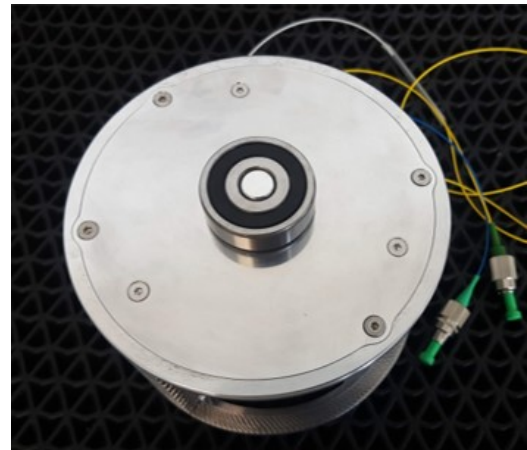
The previously mounted set was assembled on the main chassis by fastening the bottom holder to the main chassis using four screws. At this point of the assembly the front view of the prototype is presented in figure 6.16a and in the figure 6.16b the top view is shown.

6.2.6 Laser spacer assembly

The laser spacer was fastened to the top surface of the laser using three screws. In figure 6.17 the laser spacer assembly location is presented.



(a) Front view.



(b) Top view.

Figure 6.16: Assembly on the main chassis.

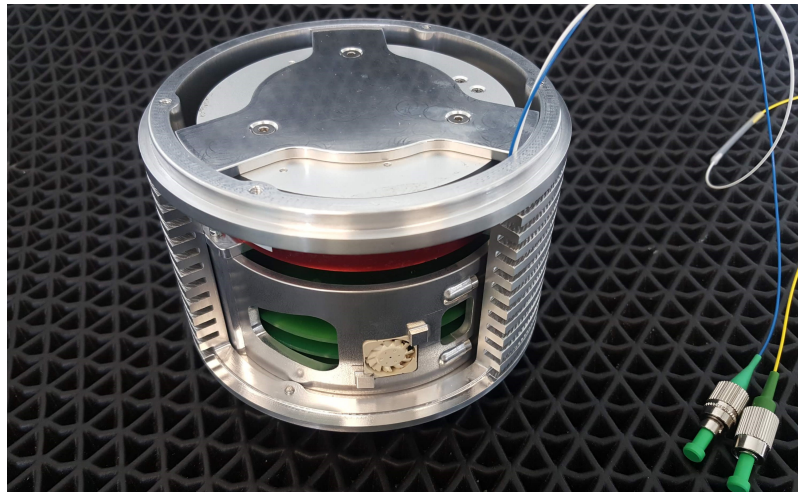


Figure 6.17: Laser spacer assembly.

6.2.7 Optics parts assembly

The optics chassis was placed at the top of the main chassis, as it is shown on figure 6.18a. Figure 6.18b displays the optics chassis placement. The fibre laser cable had to pass through the specific hole designed on these parts, as it is presented in figure 6.18b.

Afterwards, the cork part is placed at the top of the optic chassis, as it is displayed in figure 6.19.

Finally, the optics holder was placed on the top of the cork part. These optics parts (optics chassis, cork part and optics holder) were fastened to the main chassis using four screws as is presented in figure 6.20a, then the fibre laser was placed inside the optics chassis (figure 6.18b) to be used when the optic elements are positioned.

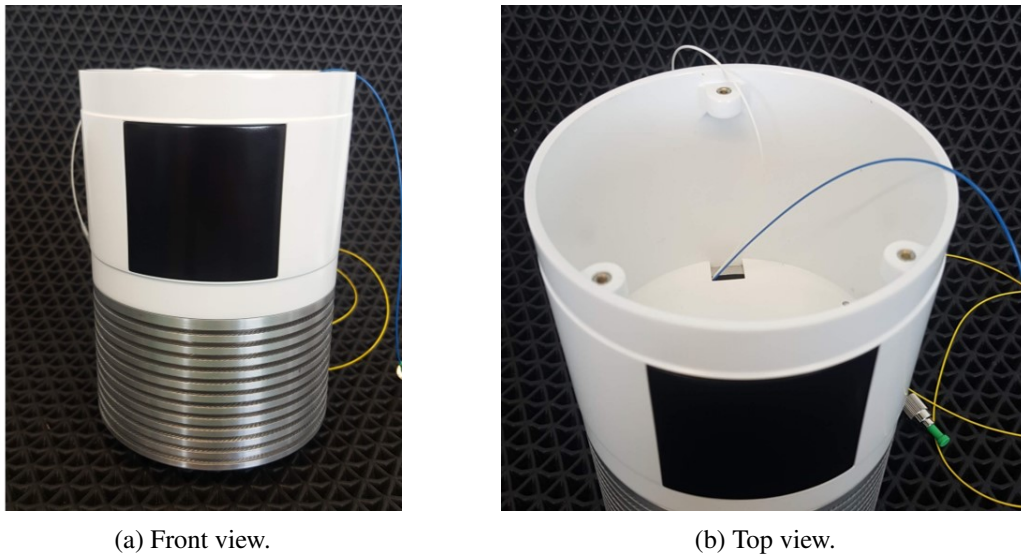


Figure 6.18: Optics chassis assembly.

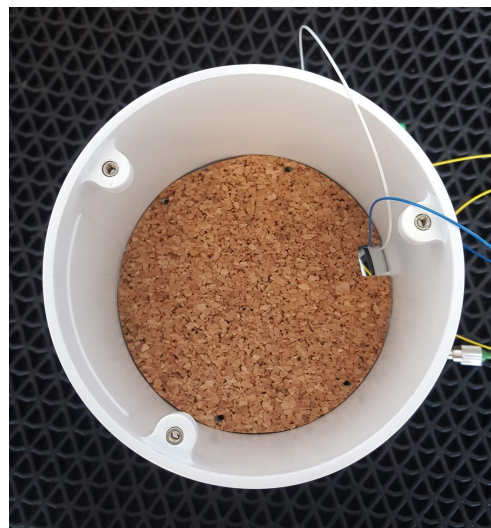


Figure 6.19: Cork part assembly.

6.2.8 Top holder assembly

The bearing was coupled on the shaft of the top holder. Then, on the top of the optics chassis was fastened the top holder using three inserts and screws, as it is presented in figure 6.21.

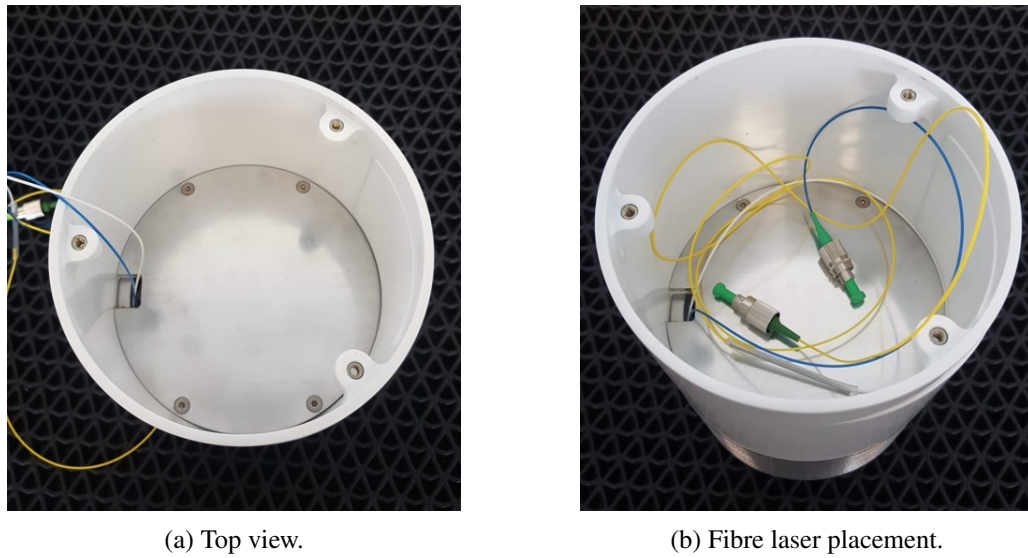


Figure 6.20: Optic chassis assembly.



Figure 6.21: Top holder assembly.

6.2.9 Final assembly

For the final prototype assembly, all the cleaning system components must be first inside the support [28]. The support has two sliding parts on the top and bottom parts that allow to fit the previously assemble parts, afterwards, the sliding parts parts are fastened using four inserts and screws. In figures 6.22a and 6.22b the final prototype assembly is presented.

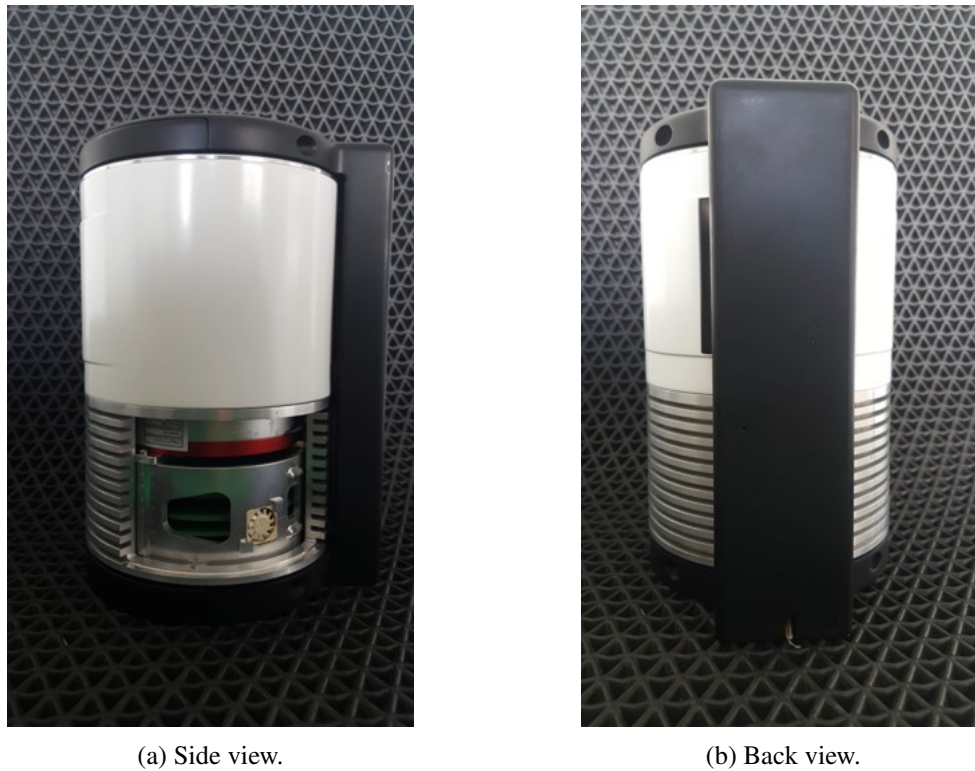


Figure 6.22: Final assembly.

6.3 System industrialization

Mass-production processes are often unsuitable for making a small number of parts, so prototypes may be made using different fabrication processes than the final product. In this application, the polymeric parts were fabricated by SLA and the metallic ones were fabricated by CNC machining and sometimes the combination of CNC machining and wire EDM, which allowed the fabrication of the parts, with the low possible cost with a tolerance that guarantees that the pieces will fit correctly in each other.

In the case of mass-production, the plastic parts could be manufacture by plastic injection moulding which requires expensive custom tooling, ensuring excellent dimensional accuracy when comparing to AM technologies. A good possibility for the aluminium alloy parts is die casting which also requires a high initial cost but has high production rates when comparing to CNC machining. Differences in the fabrication process may lead to differences in the appearance of the prototype as compared to the final product.

The materials that will be used in a final product may be expensive or difficult to fabricate, so prototypes may be made from different materials than the final product. In this case, the aluminium parts should be used in a future application. On other hand, the parts made by *Accura 25* can be replaced by another material that was presented in table 4.3.

Chapter 7

Conclusions and future works

This chapter is intended to summarize the main conclusions of the thesis, reporting the main prototype developments and results achieved. The current state of implementation and the future work to be done to improve the LiDAR system are also addressed.

7.1 Conclusions

Listed below, the main conclusions for the developed LiDAR prototype regarding the designed parts and the thermal management solutions applied are presented :

- Due to the analytic calculations, it was possible to understand that the extended surfaces enhance the heat transfer by around 67% along with the forced convection due to rotation that also increases the heat transfer by around 50%;
- According to analytic calculations, the convective effect which enhances the most the heat transfer is the forced convection due to the linear movement of the car (when the velocity is equal to 90km/h), after the forced convection due to rotation (when considering a frequency of 10Hz);
- The system fulfils the minimum operating temperature of -40°C although the maximum operating temperature of the system is 70°C instead of the 85°C defined on the automotive standards. This occurs because at 85°C the maximum operating temperature of the components is exceeded;
- According to numerical results, the applied thermal bridges on the FPGA, this is the laser holder part allows along with the PCB board ensure almost 100% of the heat is dissipated by conduction. In the case of the CoLID the dissipation through the thermal bridges (laser holder and laser spacer parts) is around 97%;

- The heat source which reveals the highest temperature, this is the most critical component on the system regarding temperature was the MAR2100 since, despite the power dissipation is low, its package was made of plastic with high thermal resistivity. Besides, no thermal management solution was applied to this component;
- Due to the numeric simulation, it was possible to understand that the fans are not appropriated for this application, representing a decrease in the average inside air temperature of only 1,28%. As future work should chosen more effective fans, where the first criteria of selection is the airflow and performance instead of the dimensions.
- The technical drawings were elaborated for all the machined parts. This implied to revise and calculate the tolerances to ensure the assembly of all parts. Due to manufacturability limitations, several designs had to be tweaked to accommodate said limitations;
- Relatively to the obtained functional prototype, all the machined parts fulfilled the imposed tolerances which allowed the successful assemble of the full prototype.

7.2 Future work

To continue developing this work, below is a list of topics that can be worked on in the future as an extension to the work provided on this dissertation:

- Vibration tests and climatic chamber tests for temperature and humidity could be performed on the final prototype ;
- Temperature monitoring for the remaining PCBs: SWIPT, μ mirror and receiver, selecting the highest heat dissipation component for each board. To estimate the power dissipation, if not in the datasheet of those components, it is necessary to use numerical simulation to iterate the power dissipation to choose the right thermal solution to be applied;
- For active thermal management solutions other solutions could be applied in a future LiDAR system, for example, thermoelectric coolers which can cool or heat the system depending on the need, with no moving parts and high reliability. However the downside of such approach could lead to high costs, low efficiency and high power consumption;
- To ensure that the system is hermetically sealed, the usage of sealants, O'rings for example, should be included;
- The EMC could be ensured by the packing of the electronic components with metallic cases;
- Further study on mesh management in order to get more feasible results when comparing with experimental results and reduce computational simulation time/load.
- Study, by numerical simulation, the influence of heat transfer through radiation;

- The usage of electronic components in which the maximum operating temperature is greater than 85°C, for example, 125°C will ensure a higher safety margin when comparing to the components which maximum operating temperature is 85 °C, avoiding failures;
- Implementation of the other subsystems not included on the prototype: Scanning, Optical and Receiving sub-system and Wireless Data and Power Transfer system.

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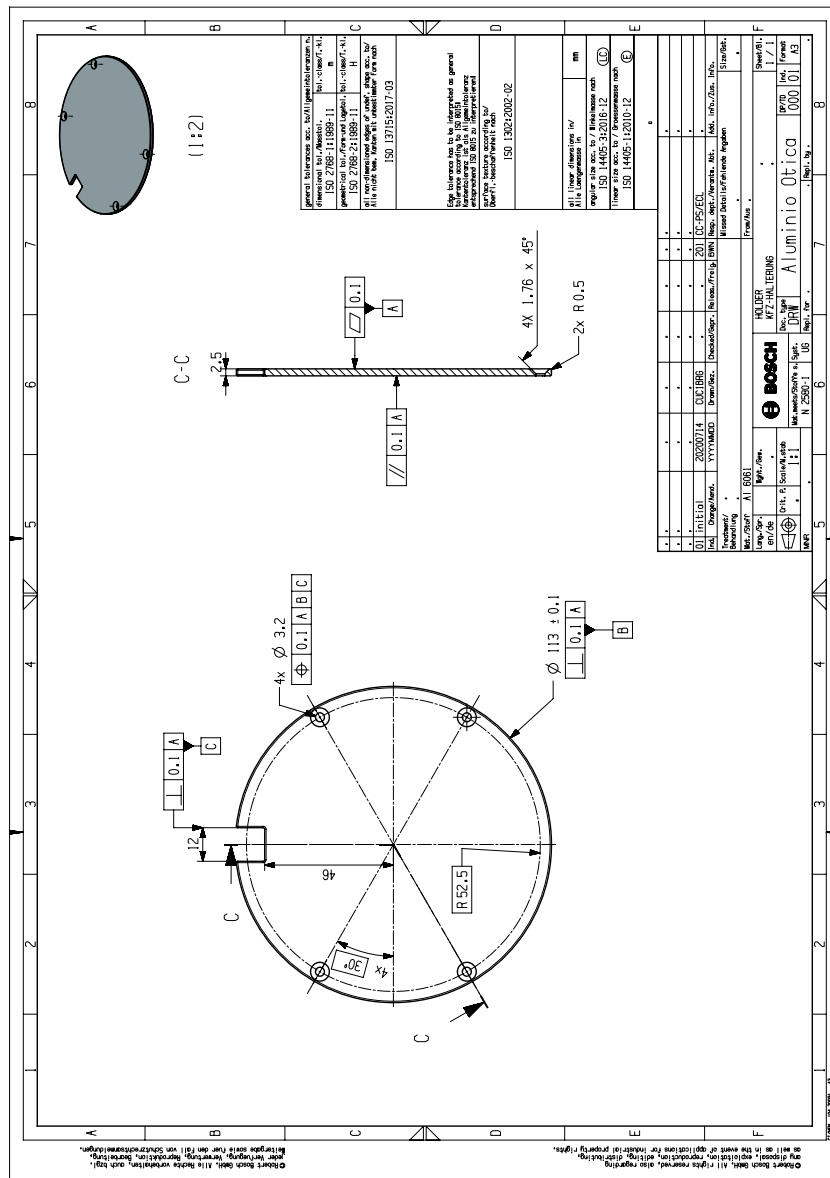
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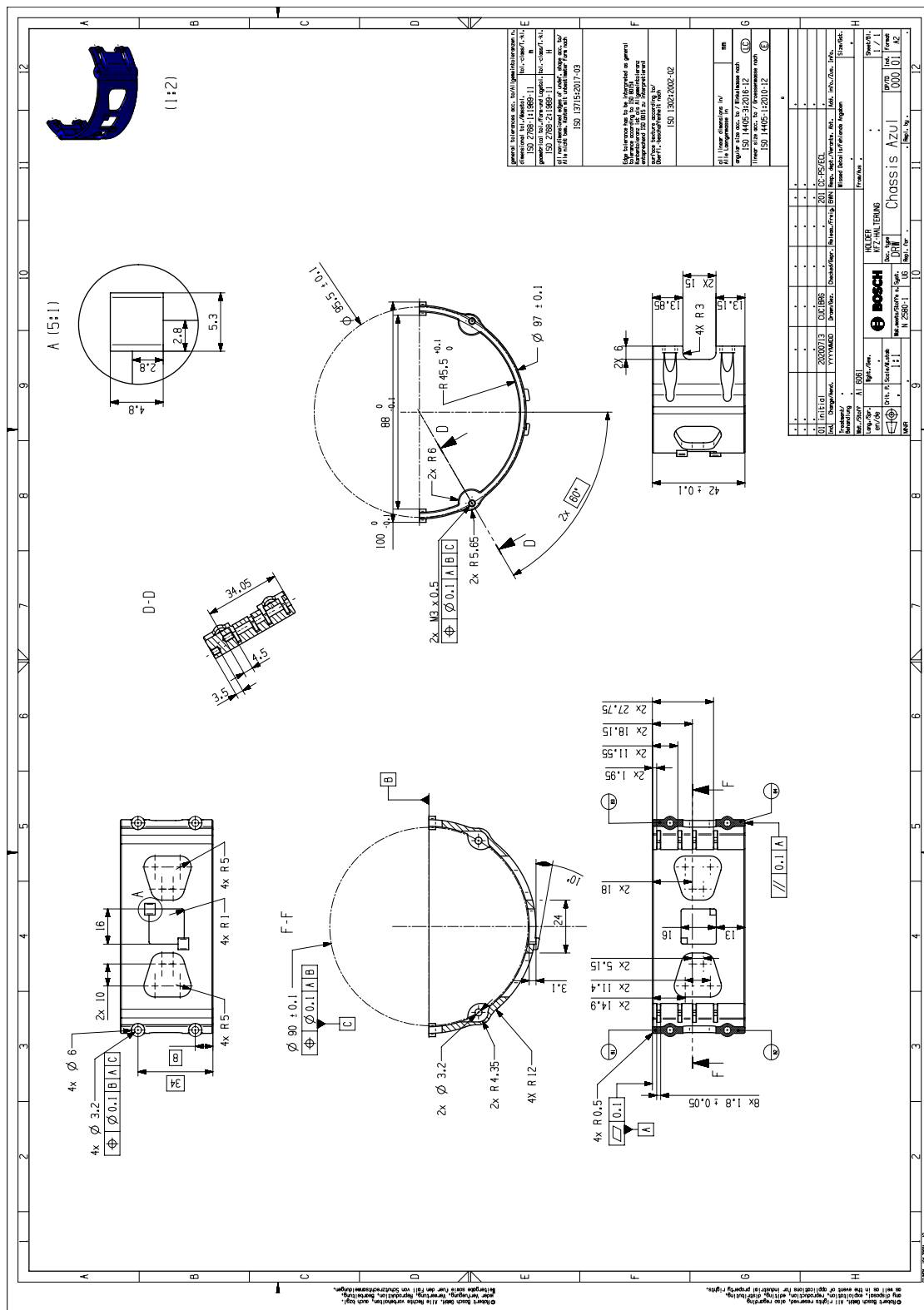
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Technical Drawings

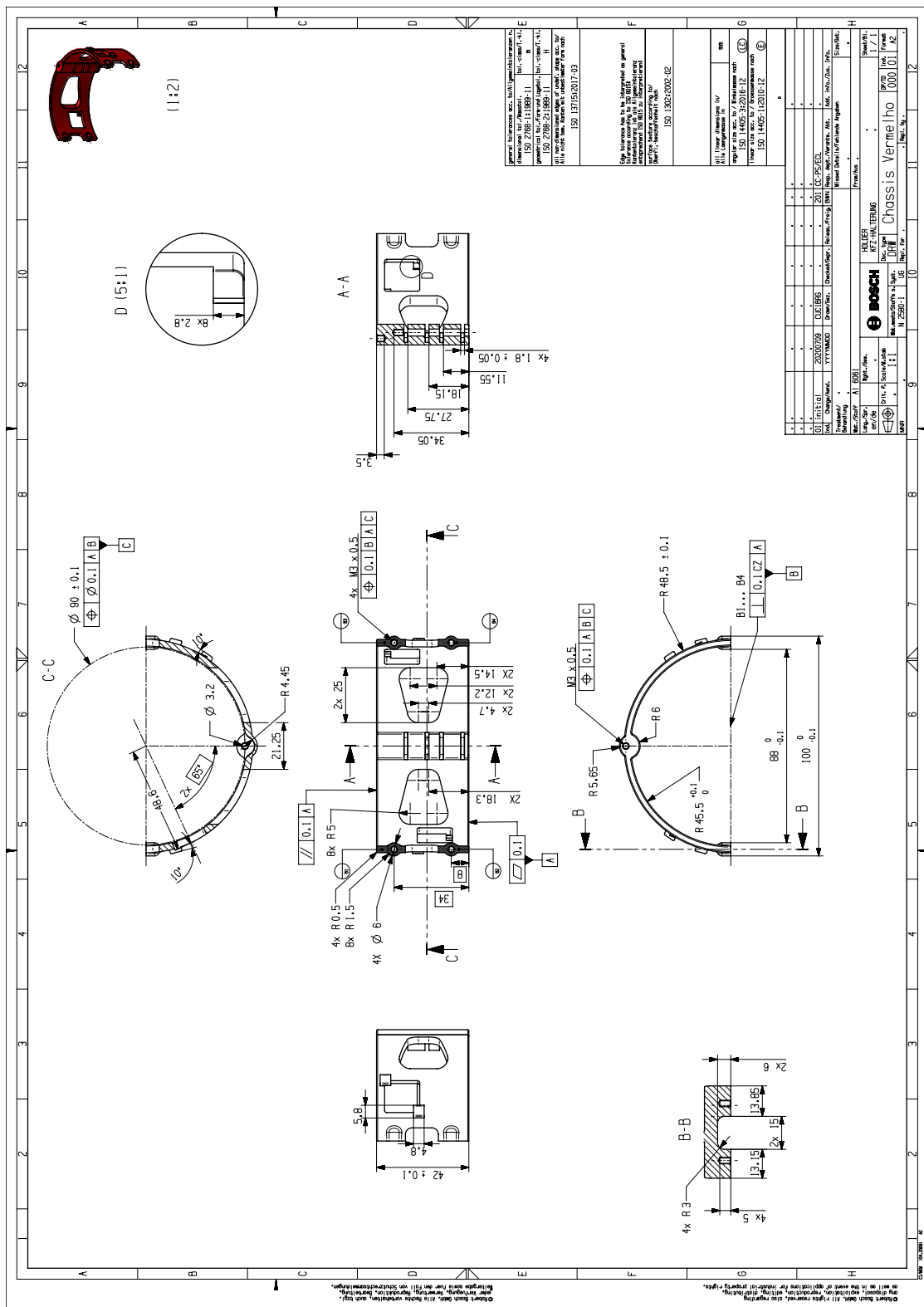
Technical drawing of the optics holder.



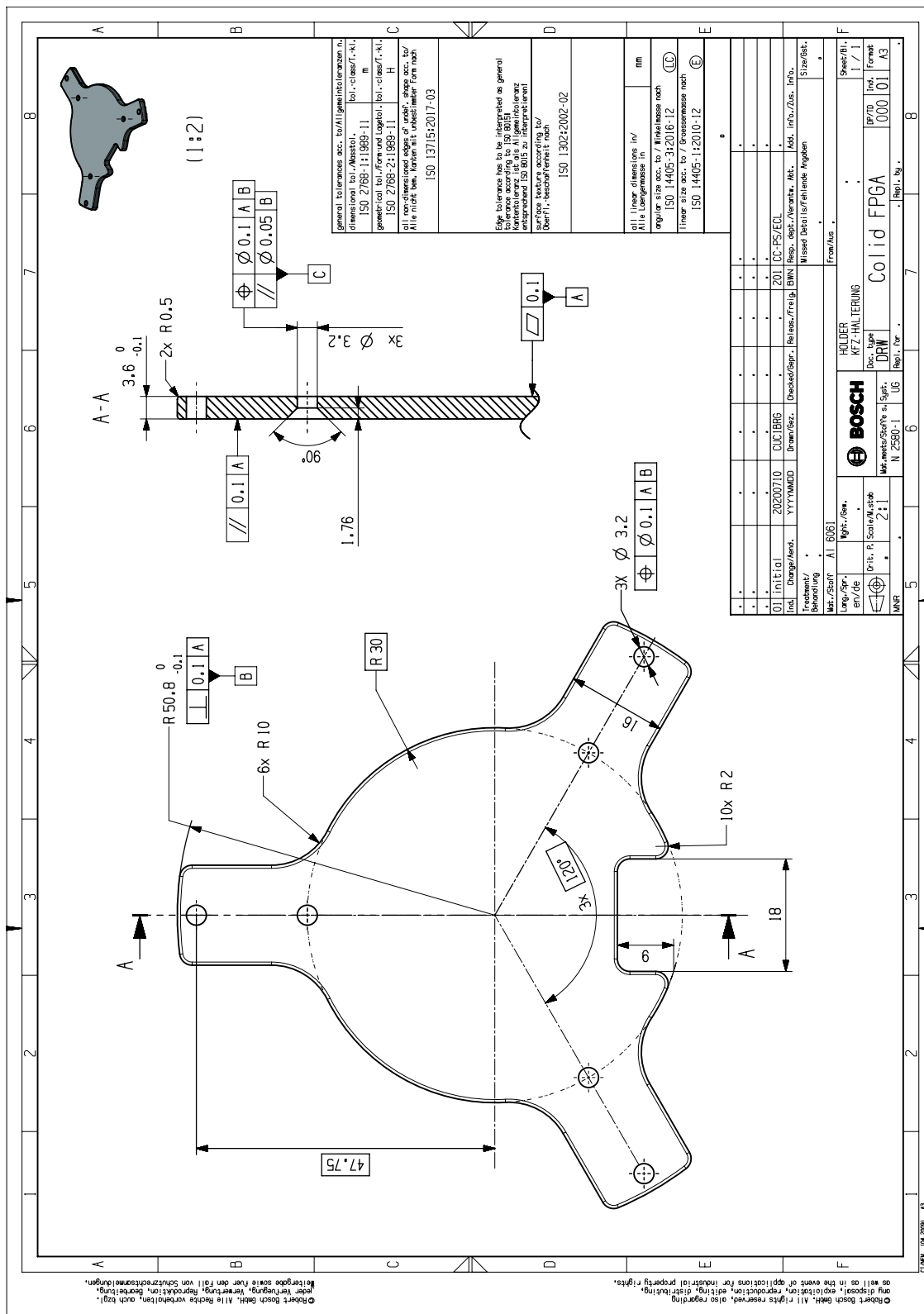
Technical drawing of one part of the PCB chassis.

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Technical drawing of one part of the PCB chassis.

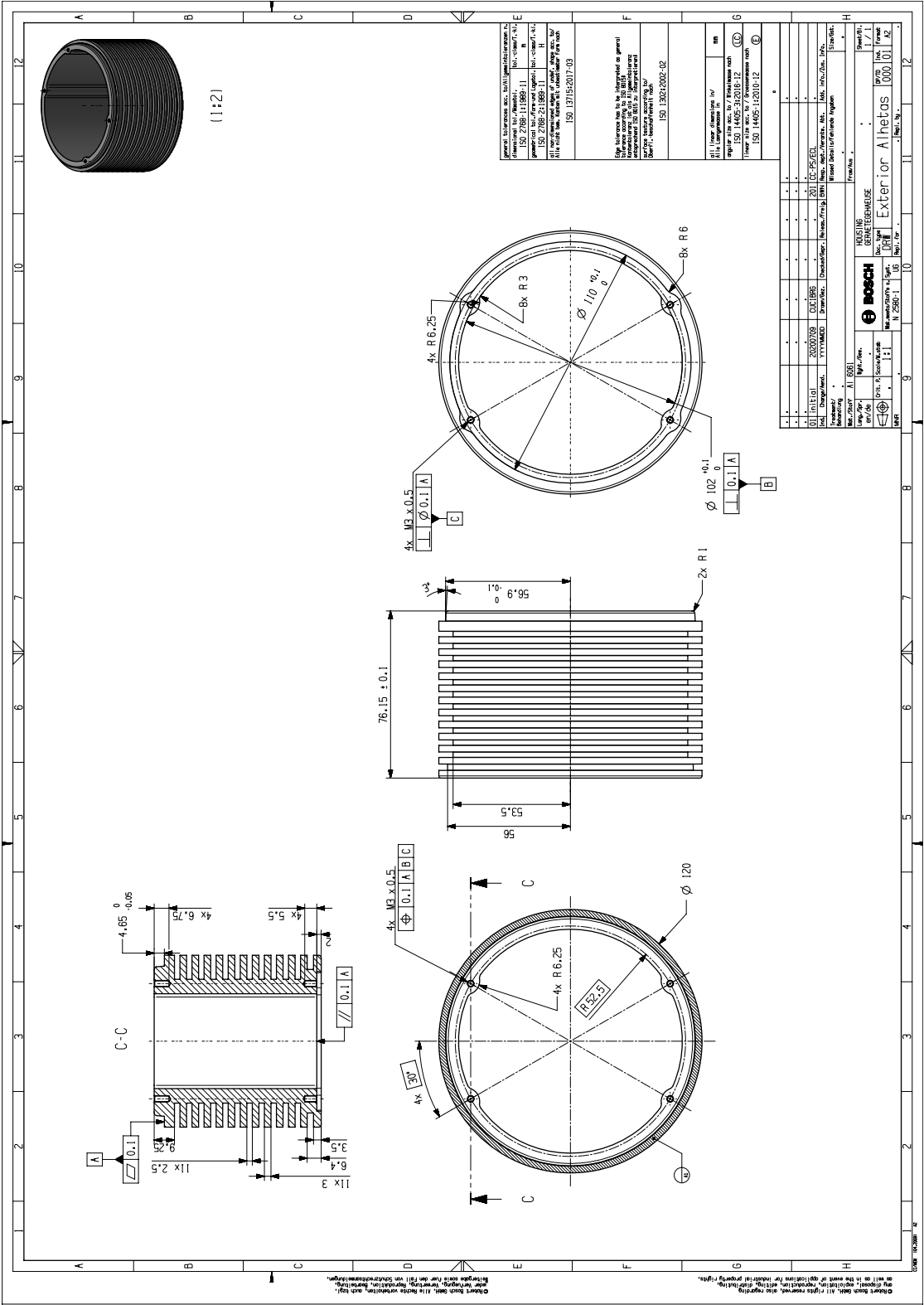


Technical drawing of the laser holder.

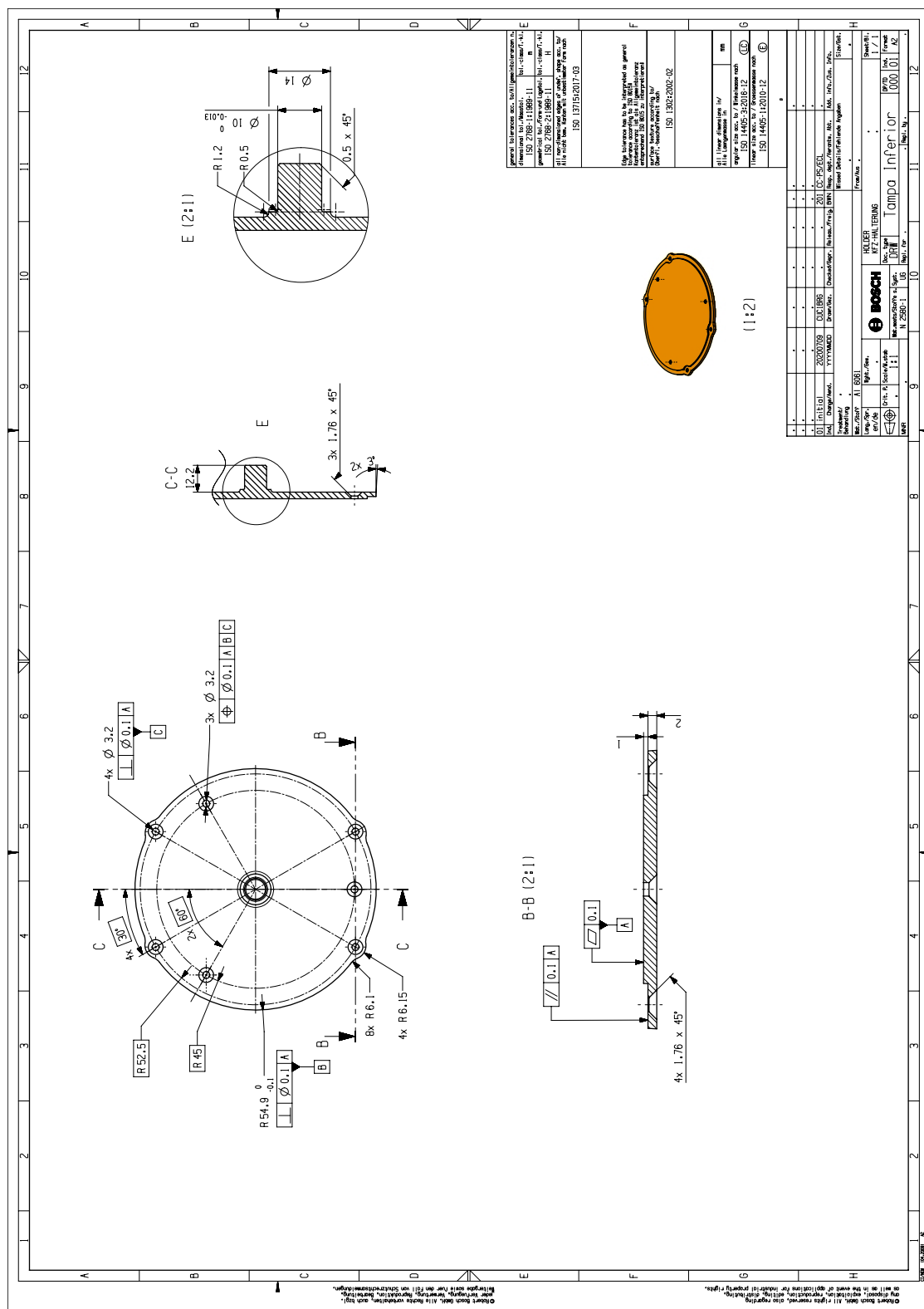


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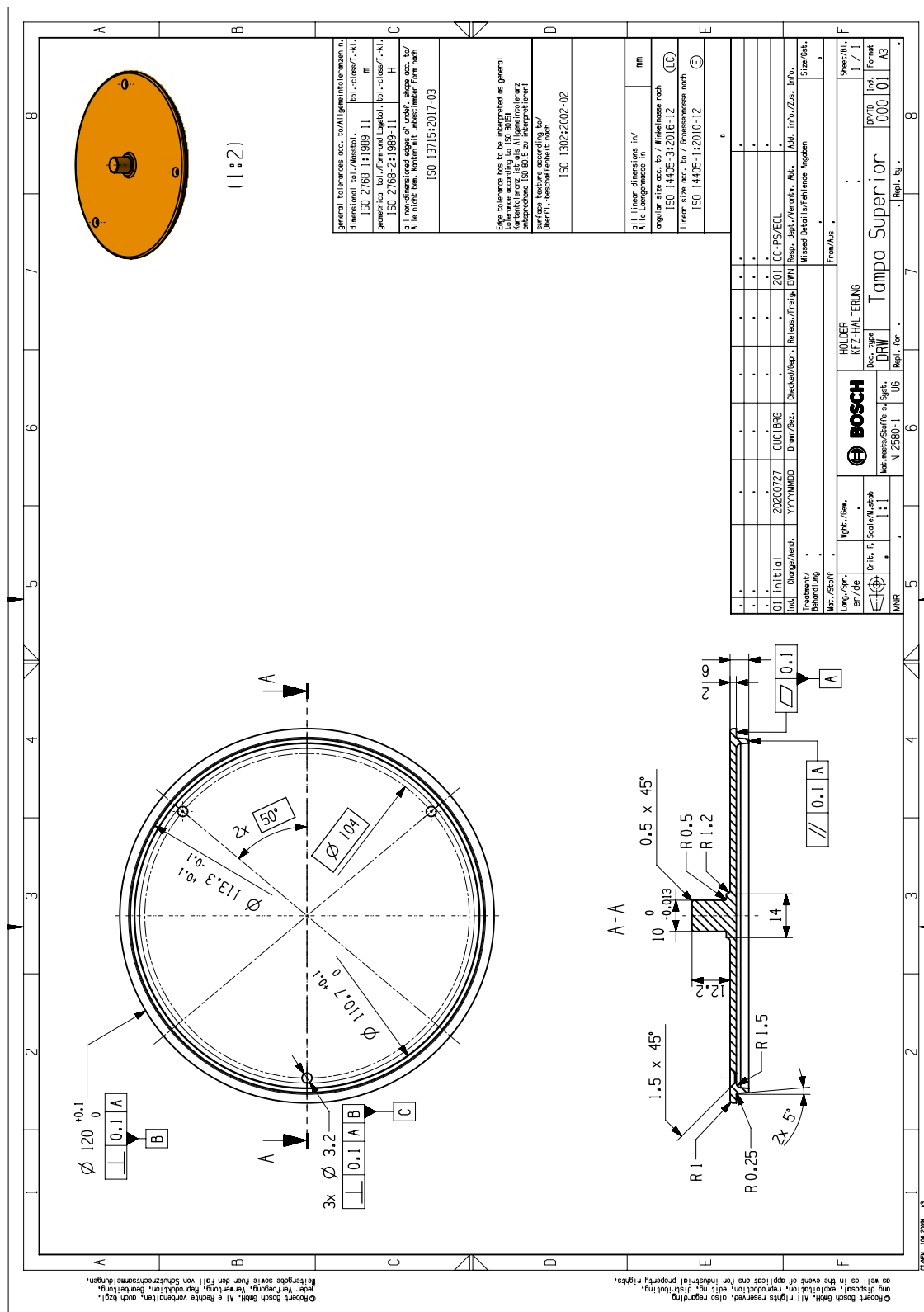
Technical drawing of the main exterior chassis.



Technical drawing of the bottom holder.



Technical drawing of the top holder



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Appendix B

Data sheets

Sunon Fan UF3F3-500 Datasheet

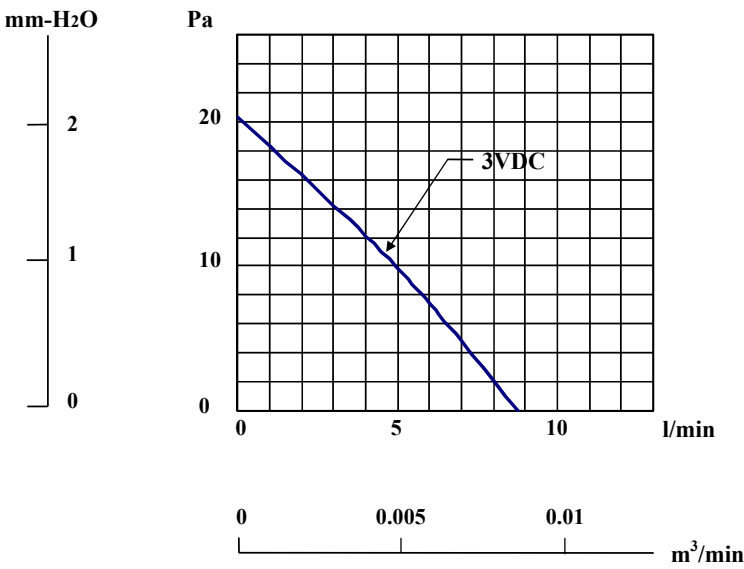
SUNON			
SPECIFICATIONS			
MODEL : UF3F3-500			
1-1. Rated Voltage	:	3 VDC	
1-2. Operating Voltage Range	:	2.0~3.5 VDC	
1-3. Starting Voltage	:	2.0 VDC (25 deg. C POWER ON/OFF)	
1-4. Rated Speed	:	14500 RPM $\pm$ 30%	
1-5. Air Delivery	:	8.75 l/min	
1-6. Static Pressure	:	20.36 Pa	
1-7. Rated Current	:	36 mA	
1-8. Rated Power	:	0.1 WATTS	
1-9. Noise Level	:	19.3 dB(A) @ 1M 30.0 dB(A) @ 0.3M	
1-10. Direction of Rotation	:	Counter-clockwise viewed from front of fan blade	
1-11. Operating Temperature	:	-10 to +70 deg. C	
1-12. Storage Temperature	:	-40 to +70 deg. C	
1-13. Bearing System	:	Vapo bearing system	
1-14. Weight	:	1.17 g	
1-15. Safety	:	CE Approvals	
1-16. Protection	:	☒ Automatic Restart Capability Note: In a situation where the fan is locked by an external force while the electricity is on, an increase in coil temperature will be prevented by temporarily turning off the electrical power to the motor. The fan will automatically restart when the locked rotor condition is released.	
	:	☒ Polarity Protection	
1-17. IP Class : IP55	:	According to IEC 529 (or IEC 34-5) IP standard, the average Temperature is 23~24°C and humidity is 67% RH for Dust Water Test. The fan needs to be test and Spray Put in dust box for 8 hours for Dust Test and be sprayed 10 minutes with water of 4 aspects for Spray Water Test. After these 2 tests, which executing by regular standard, the fan will be measured the performance is normal or not. PS. There are different applicative environments and systems by different customers, so please put the product in the most suitable environment to measure the performances.	
建準電機工業股份有限公司 SUNONWEALTH ELECTRIC MACHINE INDUSTRY CO., LTD.	SPEC.NO	D01000841F-00	REVISION DATE 01.07.2014
	ISSUE DATE	03.19.2009	E D I T I O N 8
	P A G E	3 OF 12	D.C.C. 2014.01.16 發行章

SUNON

MODEL : UF3F3-500

PERFORMANCE CURVES

STATIC
PRESSURE



建準電機工業股份有限公司 SUNONWEALTH ELECTRIC MACHINE INDUSTRY CO., LTD.	SPEC.NO	D01000841F-00	REVISION DATE	01.07.2014
	ISSUE DATE	03.19.2009	E D I T I O N	3
	P A G E	4 OF 12		2014.01.16

發行章

SUNON

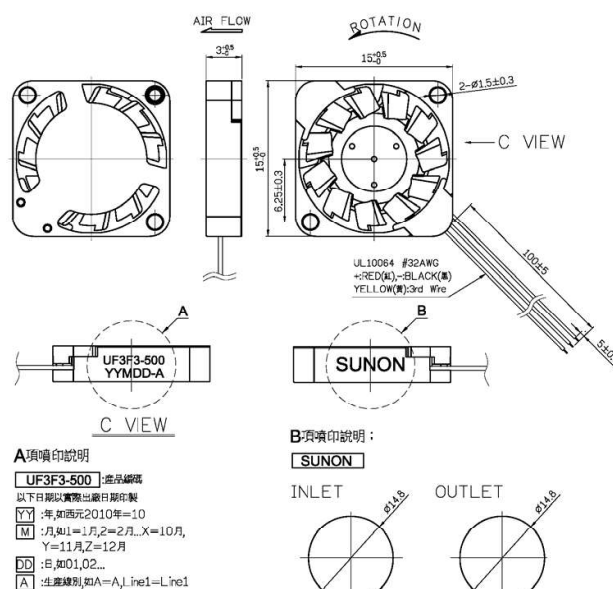
MATERIAL

- | | | |
|----------------|---|--|
| 2-1. Frame | : | Thermoplastic LCP of UL 94V-0 |
| 2-2. Impeller | : | Thermoplastic LCP of UL 94V-0 |
| 2-3. Lead Wire | : | UL10064,32 awg,+RED,-BLACK
UL10064,32 awg,YELLOW:3rd Wire |

DIMENSIONS

Note: SUNON recommends the screw and torque as below. Please contact SUNON, if any new requirement is requested.

Screw Type (Pan head)	Torque	Screw Spec	
		Size	Standard
Machine screw	0.3~0.5 Kgf-cm	M1.4	JIS B1111-1974



Sunon standard sample exclude the connector. If there is any request for connector, please advise in advance.
About recommend connector, SUNON recommend the follow models for SUNON Mighty Mini Fan/Blower:
1.(JST) SUR series connector: 02SUR-32S / 03SUR-32S / 04SUR-32S.

Best Mounting Direction: Any orientation.

UNIT: mm

建準電機工業股份有限公司 SUNONWEALTH ELECTRIC MACHINE INDUSTRY CO., LTD.	SPEC.NO	D01000841F-00	REVISION DATE	01.07.2014
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	P A G E	5 OF 12		2014.01.16

發行章

CoLID laser Datasheet

Specifications:

Parameter	Unit	Specification		
		Min	Typ	Max
Part No.		CoLID-1550		
Center wavelength ¹	nm	1540	1550	1565
Energy per pulse	μJ	-	-	30
Peak power	kW	-	-	10
Pulse average power	mW	-	-	1000
Pulse width	ns	0.5	-	200
Repetition rate	kHz	1	-	1000
Beam quality	M ²	<1.1		
Output polarization		Random		
Output power stability (15min)	%	-	-	±3
Output power stability ² (8h)	%	-	-	±1.5
Output isolation	dB	35	-	-
Operating temperature (standard)	°C	0	-	50
Operating temperature (optional)	°C	-35	-	+65
Storage temperature	°C	-40	-	85
Power consumption	W	-	-	20
Operating voltage	VDC	5.5 to 12		
Pulse-triggered mode		TTL External trigger		
Length of output pigtail	m	>0.3		
Output termination		FC/APC or Collimator		
Dimension	mm	90x23.5 (D x H)		
Weight	g	<300		

Specifications:

Ordering information:

- Other wavelengths are available;
- The output power stability is measured under 25°C, after 30 minutes' warm-up.

- CoLID-1550-XX-YY-ZZ-FA
- XX: Pulse width in ns
- YY: Repetition rate in kHz
- ZZ: Peak power in KW
- FA: FC/APC connector, Collimator (Co) is optional.
- Example: CoLID-1550-07-20-04-FA
- CoLID- I series 1550nm Pulse Fiber laser module, 7ns pulse width, 20kHz repetition rate, 4kW peak power, FC/APC connector.



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CONNET LASER TECHNOLOGY CO., LTD.

Appendix C

Materials

Aluminium AW 5083

WWW.AMAS.PT

PLACAS LAMINADAS

AW 5083

H111 LAMINADO

Densidade 2,7 g/cm³

[AL Mg4,5Mn0,7]

PLACAS LAMINADAS

AW 5083

H111 LAMINADO

Densidade 2,7 g/cm³

[AL Mg4,5Mn0,7]

PRINCIPAIS CARACTERÍSTICAS

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

APLICAÇÕES

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

PROPRIEDADES QUÍMICAS

EN 573-3

	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al mm.		
										Outros	Total	Restante
EN AW 5083	0,4	0,4	0,1	0,4-1,0	4,0-4,9	0,05-0,25	-	0,25	0,15			
	0,4	0,4	0,1	0,4-1,0	4,0-4,9	0,05-0,25	-	0,25	0,15			

PROPRIEDADES MECÂNICAS

EN 485-2

Estado metalúrgico da amostra	Espessura especificada mm	Tensão de ruptura à tração (Rm) MPa		Tensão de cedência (Rp0,2) MPa		Extensão após ruptura min. %	Alongamento após ruptura min. %	Dureza HBW	
		Superior a	inferior a	min.	max.				
H111	0,2	0,5	275	350	125	11	1,01	0,51	75
	0,5	1,5	275	350	125	12	1,01	1,01	75
	1,5	3,0	275	350	125	13	1,51	1,01	75
	3,0	6,3	275	350	125	15	1,51	1,51	75
	6,3	12,5	270	345	115	16		2,51	75
	12,5	50,0	270	345	115				75
	50,0	80,0	270	345	115				73
	80,0	130,0	260	310	110				70
	130,0	200,0	255	105	12				69
	200,0	250,0	250	95	10				69
250,0	300,0	245	90	9				69	

STOCK AW 5083 LAMINADO

PLACA

ESPESURAS

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

Para outras dimensões consulte-nos. Corte sob medida.

Aluminium AW 6082

WWW.KIMS.PT

PROPIEDADES MECÂNICAS

EN 485-2

	Tempera	Diâmetro	Rm Mpa min.	Rp0.2 Mpa min.	A% min.	Dureza HBW
Cilindrado	T6	≤ 80	310	255	10	95
	T6	≤ 150	310	260	8	95
Extrudido	T6	150 < D ≤ 200	280	240	6	95
	T6	200 < D ≤ 250	270	200	6	95

STOCK BARRA REDONDA AW 6082

BARRAS REDONDAS

Ø DIÂMETRO

20 mm	25 mm	28 mm	30 mm	35 mm	40 mm
45 mm	50 mm	60 mm	65 mm	70 mm	80 mm
90 mm	100 mm	110 mm	120 mm	135 mm	150 mm
200 mm	254 mm	350 mm			

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



BARRAS REDONDAS

AW 6082

BARRA REDONDA

[AL Si11MgMn]
Densidade **2,8 g/cm³**

PRINCIPAIS CARACTERÍSTICAS

- Resistência mecânica moderada
 - Maquinabilidade moderada
 - Boa resistência à corrosão
 - Ideal para anodização
 - Boa soldabilidade
- APLICAÇÕES
- Indústria metalúrgica
 - Parafusos
 - Barras roscadas
 - Componentes para máquinas

PROPIEDADES QUÍMICAS

EN 573-3

EN AW 6082	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
	0,7 - 1,3	0,5	0,1	0,4 - 1,0	0,6 - 1,2	0,25	-	0,2	0,1
	Ga	V	Observações	Outros		Al min.			
-	-	-	-	Cada	Total	Restante			
				0,05	0,15				

Accura 25

STEREOLITHOGRAPHY

Accura® 25 Plastic

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

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

Todd Reese, President
Realize Inc.

**Technical Data****Liquid Material**

Measurement	Condition	Value
Appearance		White
Liquid Density	@ 25 °C (77 °F)	1.13 g/cm ³
Solid Density	@ 25 °C (77 °F)	1.19 g/cm ³
Viscosity	@ 30 °C (86 °F)	250 cps
Penetration Depth (Dp)*		4.2 mils
Critical Exposure(Ec)*		10.5 mJ/cm ²
Tested Build Styles		EXACT™, FAST™, EXACT™ HR

Post-Cured Material

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

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



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PN 70668 Issue Date - April 08