Lappeenranta-Lahti University of Technology LUT
LUT School of Energy Systems
Degree programme in Mechanical Engineering

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DESIGN OF WOOD CHIP MEASUREMENT SYSTEM

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TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT
LUT School of Energy Systems
Konetekniikan koulutusohjelma

Toni Toivanen

Hakeskannerin suunnittelu

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81 sivua, 23 kuvaa, 15 taulukkoa ja 4 liitettä

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Tässä diplomityössä esitellään hakeskannerin kehitystyö. Skanneri mittaa hakkeen laatua, palakokoa ja tilavuusvirtaa kuljettimella. Datasta on hyötyä sekä hakkeen tuottajalle että käyttäjälle – sitä voidaan käyttää muun muassa prosessinohjaukseen ja hinnan määrittämiseen.

Tärkein tavoite oli kehittää hakeskannerin kokonaisratkaisu. Tavoitteen saavuttamiseksi valittiin mittalaitteet ja suunniteltiin niiden muodostama toiminnallinen kokonaisrakenne, sekä ratkaistiin lian, värinän ja ympäristön lämpötilanvaihteluiden aiheuttamat ongelmat.

Työn teoreettinen pohja perustuu systemaattiseen tuotesuunnitteluprosessiin. Prosessia täydennettiin värähtelyanalyysilla, lämpöanalyysilla ja DFMA:lla. Lisäksi teoriaa hyödynnettiin mittaustekniikasta, materiaalinvalinnasta ja kokeellisesta suunnittelusta.

Työn tuloksena on valmis hakeskannerin malli. Lisäkehitystä kuitenkin vaaditaan, kun se valmistetaan ja testataan prototyyppinä.

ABSTRACT

Lappeenranta-Lahti University of Technology LUT
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Design of wood chip measurement system

Master’s thesis

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81 pages, 23 figures, 15 tables and 4 appendices

Examiner: Professor Harri Eskelinen
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Keywords: wood chip, scanning, measuring

This master’s thesis presents the design process of a wood chip scanner for measuring chip quality, dimensions, and volume flow on conveyor. Data is valuable both for the producer and purchaser of chips – it can be used as feedback data for process control and basis for price-determination.

Main goal of the research was to invent an overall solution of the chip measurement system. To achieve the goal, measurement instruments were selected, and overall functional structure was designed around them. Also, problems caused by dirt, vibration and ambient temperature variations were solved.

The theoretical base is built upon systematic product design process. It was complemented with individual methods such as vibration analysis, thermal analysis and DFMA. Theory of measurement technology, material selection and experimental design were utilized as needed.

Complete design of chip scanner was achieved as result. However, further development is needed after it is manufactured and tested as prototype.

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Toni Toivanen

Toni Toivanen

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Area of thermal surface [m^2]
c	Circle of Confusion [mm]
f	Focal length [mm]
h_o	The coefficient of heat transfer by long wave radiation and convection and outer surface [no unit]
I_t	Total solar radiation incident on surface [W/m^2]
N	F-number of optical system [no unit]
R	Thermal resistance [m^2K/W]
t_e	Sol-air temperature [°C]
t_o	Outside temperature [°C]
u	Distance to object in photography [mm]
α	Absorptance of surface for solar radiation [no unit]
δR	The difference between long wave radiation incident on surface from sky and surroundings and radiation emitted by black body at outdoor air temperature [no unit]
ε	Hemispherical emittance [no unit]
ω	Excitation frequency [Hz]
ω_n	Natural frequency of system [Hz]

CCD	Charged Coupled Device
CHS	Circular Hollow Section
CMOS	Complementary Metal Oxide Semiconductor
DFMA	Design for Manufacturing and Assembly
DOF	Depth of Field
IP	Ingress Protection
PSD	Power Spectral Density
RHS	Rectangular Hollow Section

1 INTRODUCTION

The goal of this research is to design a wood chip scanner for online measurement of chip dimensions, quality, and volume flow on a conveyor. The measured data is to be used as feedback data to chipping process and aid control of pulping process. Need for this study comes from Finnos Oy, a Lappeenranta-based company specialized in industrial X-Ray and machine vision solutions.

1.1 Pulping process and importance of chip quality

Wood chips are used, among other materials in the pulping process as the source of fibers. In chemical pulping process, heat, chemicals, and mechanical treatments are used to separate fibers from the material. Also, a purely mechanical pulping process exists. Regardless of the process used, properties of the pulp produced depends largely on the chemical and structural properties of the wood chip raw material. (Sixta 2006, p. 3)

According to Bjurulf (2006, p. 17) the structural properties of chips that are particularly interesting in manufacturing of pulp are as follows:

- “Moisture content
- Bark content
- Chip dimensions, described according to screen classifications
- Discoloration
- Contaminations (i.e stones, sand, plastic, metals etc)”

There are benefits from utilizing chip scanning, both for the producer- and purchaser of chips. When considering the point of view of producer, they will gain great benefit from being able to control the chipping process in real time. Adapting to changing factors such as wear of the chipper tools and varying raw material can be done more versatilely. For the purchaser of chips, such as a pulp mill, the main advantage is being able to control the pulping process using online measurement data.

Recommended chip size is depicted in Figure 1. Chips must be roughly uniform in size and follow the optimal size guideline. Cooking time depends directly on how fast the chemicals penetrate the material. Therefore, larger chips require a longer cooking time. Doubling the chip length will result in 4 times longer cooking time. If the chip size variation in one batch is large, the smaller chips may consume majority of the chemicals and prevent larger chips from getting proper saturation. (Sixta 2006, p. 79)

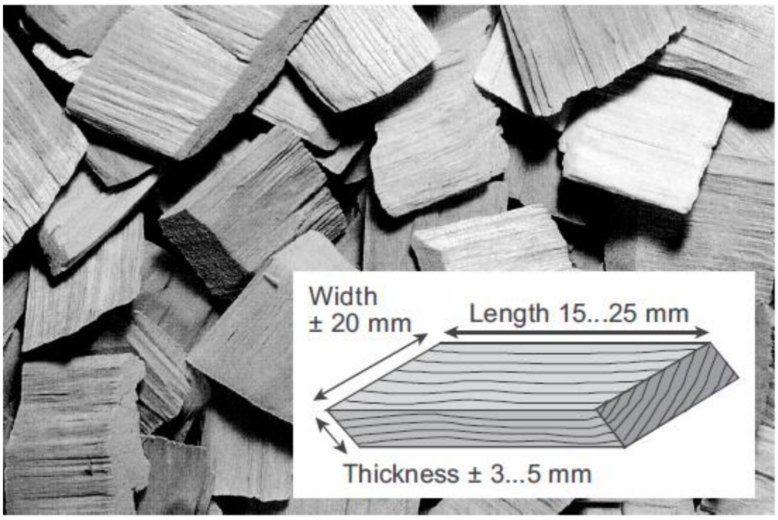


Figure 1. Recommended wood chip dimensions for pulping (Sixta 2006, p. 80)

Bark content and discoloration are properties that can affect brightness of pulp and deteriorate printability of the resulting paper. Previously mentioned factors, as well as total volume of the chips can be easily used as price-determining properties in chip market. Therefore, it is important to measure precisely and automatically.

There are existing products for chip measurement on the market. Most solutions only consider a small sampling flow of chips and not entire conveyor. Even totally manual methods, such as catching chips in a bucket and running them through a set of sieves are used in process control. In this case, a couple of wood chip buckets might represent a day worth of chips, leading to great inaccuracy.

1.2 Scope

Main practical problem is that the there is no overall solution to be used in this application. Other scanners in the lineup of target company are not directly suitable for this market. On the other hand, the features of other products that are proven functional will be implemented to chip scanning.

The goal of the research is to invent an overall solution to fulfill the objective and produce complete 3D model of the industrial chip scanner. Study will not include any automation or software design – the focus will be on mechanical system. The 3D model must be mature enough to proceed straight to manufacturing documents and production.

1.3 Research problem

Research problem originates from inaccuracies in measurement caused by vibrations, temperature variations and dirt. Solutions to those must be developed during this study.

1.4 Research questions

The main research question is as follows: How to design a modular chip scanner that scans entire chip flow unaffected by environmental factors and using different measurement technologies integrated together?

The main research question can be divided into smaller sub-questions that the research aims to find answers to:

- What is the best solution for complete scanner design, including instrument frames, mountings, protective shell, installation mechanism and electrical routings?
- What factors affect the interference to laser scanning caused by light and how to prevent them?
- How to prevent any harm to measurement caused by vibrations, temperature variation and dirt?
- How to choose measurement instruments for this application?

1.5 Research methods

Literature review is used to find information on design processes and other theory that are utilized during study.

2 THEORY AND METHODS

In this section, the theory basis and methods used during work are described. A summary of existing measurement technology is covered, along with product development process and other means of design.

2.1 Overview of measurement technology

This chapter is based on previous work of the target company, as well as data available from equipment manufacturers. Having a basic understanding of measurement instruments and related technology is basic requirement for being able to use them correctly.

2.1.1 Laser triangulation

Laser triangulation is a measurement technology that uses a laser projected at object and a camera to observe the laser line or point. Camera is located offset and angled differently from the laser source. Therefore, it is possible to determine distance from scanner to the surface to be measured. (AZoSensors 2014)

In some cases, it is enough to use a point laser – in that case the sensor is a simple distance sensor (one dimension). When a line laser is utilized instead, the resulting scan is a 2D surface. In order to achieve a 3D shape, either the scanner or object is moved and multiple 2D profiles are captured. When compiling the 2D-surfaces together, 3D shape is formed.

Geometry properties, such as clearance distance, measurement range and field of view (Figure 2) are specified by scanner manufacturers and can be used to evaluate scanners suitability for certain use case. The properties are governed by the type of laser, camera sensor and optics that are used. Clearance distance is the distance from scanner to the nearest object that can be measured. Measurement range is the range of measurement, starting at the clearance distance and ending at the distance at which the object is too far away to measure. Field of view specifies the width of scannable area. Due to the shape of the laser fan, field of view in dependent on distance from sensor – it becomes wider when moving away from sensor.

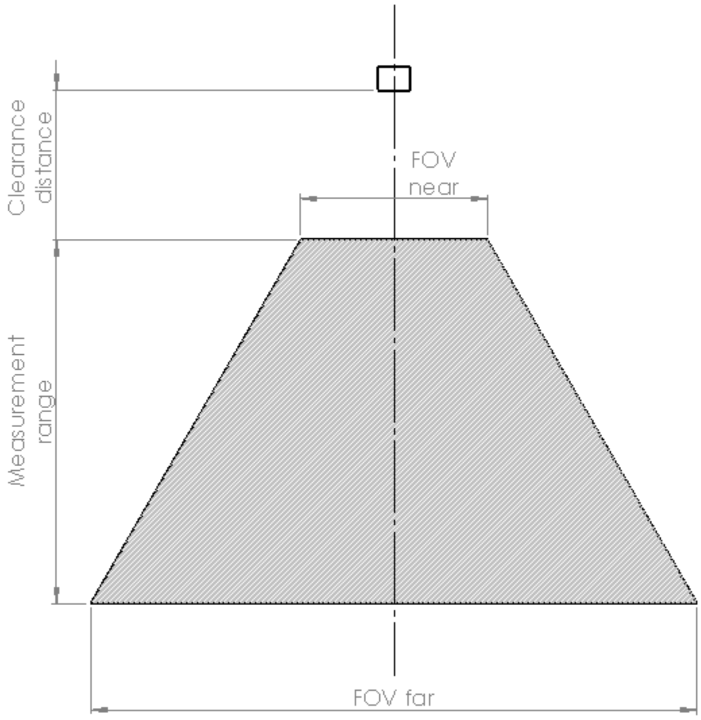


Figure 2. Typical scanning area shape of a laser scanner

Laser safety classes and guidelines are controlled by IEC standard 60825. Whether the laser beam needs to be protected from human sight depends on the laser class. Interlocking requirements and safety labelling are also specified in the standard. Some types of lasers require a key operated control.

Laser classes 1 and 1M are considered safe to the human eye, although 1M prevents use of optical instruments when viewing. They work in the wavelength range from 302,5 nm to 4000 nm. Laser class 2 and 2M allow for higher power rating but are restricted to function in the wavelength range of visible light: 400 nm to 700nm. These classes rely on blinking reflex of human eye to be considered safe, hence the requirement for visibility. Classes 3R and 3B are hazardous to view but diffused reflections are safe, whereas for class 4 laser devices even the diffused reflections are dangerous to view. (IEC 60825-1 2001, p. 47-49)

In this application, laser-based measurement is needed to measure the volume flow of wood chips. With certain accuracy, it could be also be used to measure dimensions of individual chips.

2.1.2 Color imaging and optics

Cameras are devices used to capture image. They most commonly consist of an objective and camera frame. The ordinary machine vision camera frame includes shutter, sensor, mounting for objective, electrical connectors, and control electronics. Objective is made up from a system of one or more lenses, and systems for focus adjustment and aperture adjustment. Cameras capable of capturing image with color included are called color cameras.

CCD (Charged Coupled Device) and CMOS (Complementary Metal Oxide Semiconductor) are two commonly used sensor types in digital imaging. They work by converting light into electric signal. Both technologies have unique strengths and weaknesses depending on the application: in some use cases CCD may be superior to CMOS and vice versa. For machine vision use, speed and noise of sensor are important factors. According to the article, CMOS sensor is superior in both aspects to the CCD, which is said to be technology of the past. (Teledyne DALSA n.d.-a)

Sensors come in matrix and line form. Matrix sensor features array of pixels in 2D plane. Line sensor is effectively one-dimensional, and the second dimension of image comes from the object moving perpendicular past the sensor. The cost of resolution in line-scanning application is lower than matrix camera and allows for better imaging of objects moving at high speed. (Teledyne DALSA n.d.-b)

Lens is a component used to form the image on sensor. The most important properties of the lens are focal length and aperture. In machine vision, focus adjustment is commonly done by adjusting the lens manually. F-number is commonly used property to describe aperture. It is defined as the ratio between focal length of the lens and diameter of entrance pupil (Allen & Triantaphillidou 2012, p. 112).

Depth of field (DOF) is the range of distance within the target appears to be sharply focused. Allen & Triantaphillidou (2012, p. 111) provide the following formula for estimating DOF:

$$DOF = \frac{2u^2Nc}{f^2} \tag{1}$$

In equation 1, u is the distance to object, N is f-number, c is circle of confusion and f is focal length. Values for circle of confusion, the criterion of permissible unsharpness, can be found tabled for different sensor formats (Allen & Triantaphillidou 2012, p. 111).

A good amount of light is required to achieve high quality images, especially if the objects are moving. When light level is too low, higher exposure needs to be used, leading to blurring. Another way to cope in low lightning is to increase the aperture but doing this leads to smaller depth of field and object is more likely to appear out of focus. Optimal quality is achieved when light level is high, and aperture and exposure time can be kept low.

In this application, color imaging is needed to measure chip dimensions and quality. It can be used as method alongside laser to determine individual chip size. Also, chip discoloration and bark content could be determined.

2.1.3 Rotary encoder

Rotary encoder is a device that converts rotational movement into electric pulses. Pulses are used to measure changes in angular position of the shaft. This is particularly useful in measuring applications when tracking location of objects moving on a conveyor by installing it to the drive shaft of conveyor.

There are multiple technologies the encoder can be based on, including optical, magnetic, and capacitive. The most used type is optical, which will be covered in more detail in this study. At simplest form, it consists of a light source, codewheel and light transmitting sensor. Term photointerrupter is used for the light source and transmitter combination. Codewheel is mounted so that it spins at same rate as the shaft to be encoded and features a pattern of holes. As the shaft turns, the codewheel blocks and lets light through alternatingly, resulting in a pulse train. (Bishop 2002, p. 377-378)

Light sources and transmitters are often large compared to the holes in code wheel. In order to sharpen the edge of light arriving to the light sensor, a stationary code wheel (mask) is used in addition to the turning one. Figure 3 illustrates the arrangement of encoder components. (Machine Design 2002)

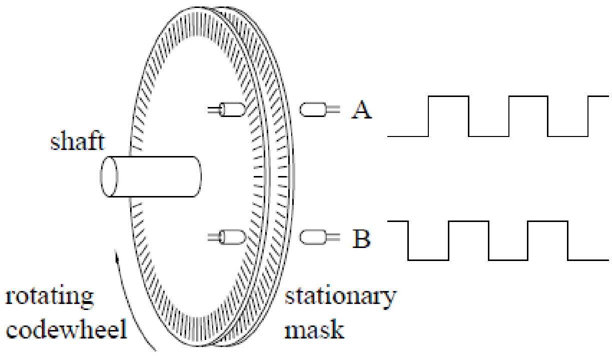


Figure 3. Schematic of optical rotary encoder (Bishop 2002, p. 377)

In most cases, the encoder is equipped with two photointerrupters, resulting in two independent pulse trains with a phase difference. Turning direction of shaft can be determined based on out-of-phase signals. Encoders can be divided to two different types: incremental and absolute. Incremental encoders are only reporting how much the shaft has turned relative to the starting position - it is impossible to know absolute angle of the shaft. Absolute encoders are equipped with codewheel patterned so that a combination of pulses generated is unique to the angular position of the shaft.

Motion axes that are based on incremental encoder achieve somewhat precise location information provided that the axis is zeroed using a limit switch. Even in this case, location information is lost and must be homed again if system is powered off or encoder signal is lost due to electrical interference. Encoding is needed in machine vision systems that work with objects that are moving, such as logs or wood chips, transported on conveyor.

2.1.4 Measurement process

Measurement devices that obtain a 2-dimensional (*X* and *Y*) point cloud use the encoder data (*Z*) to form a 3D point cloud. In measurement applications encoder resolution must be high end entire conveying mechanism must be well constructed so that encoder data matches actual object movement as closely as possible. For example, if the encoder is mounted to a driving pulley of a belt conveyor, it must be ensured that no slipping occurs between belt and pulley or between belt and conveyed product.

Control unit is used to capture signal from encoder and command cameras to obtain frames at correct moment. Therefore, measurement is independent on how fast the conveyor is driven, provided that the framerate of cameras is enough.

2.1.5 Precision

According to previous research conducted by the company, isolation of vibration and temperature are key factors when pursuing excellent measuring accuracy. Vibration causes irregularities in the measured data from most instruments, including laser scanners and common cameras. Instrument frames and mountings may suffer from parts shaking loose leading to misalignment of measurement device. Some measurement instruments are prone to breaking due to vibration. Keeping the temperature stable is beneficial for both measurement accuracy and keeping electrical components from overheating or running at too cold temperatures.

2.2 Systematic product development process

Product development is a complex task and the variety of methods that must be utilized is large. Not using a controlled process would result in too many possible choices to be handled. Therefore, it is crucial to follow a design process and learn correct use of individual methods. (Pahl & Beitz 2007, p. 126)

There are numerous design processes for use that are widely available and well researched. The most common ones are, according to Childs (2019, p. 4) are the total design process, systematic design process, CDIO (conceive, develop, implement, operate), double diamond, six sigma and many more. Design engineering is not exact science and there is no one proven process to guarantee success to any design problem. For this task, the systematic product design process is chosen, as it is well established and familiar to the author.

Designing a product is described by Pahl & Beitz (2007, p. 129) as repetitive information processing during which each step brings the result closer to desirable result. One of the purposes of systematic design process is to minimize the number of iterations needed to reach satisfying result. Process suggested by above-mentioned authors consists of following main phases:

- “Planning and task clarification: specification of information

- Conceptual design: specification of principle solution (concept)
- Embodiment design: specification of layout (construction)
- Detail design: specification of production."

It must be noted that in real cases, these main phases may not be distinguished from each other. Some fine details might be decided early in the process. It is also possible that as the process advances, some new auxiliary requirement arises, and steps must be taken from the beginning to fulfill it.

To clarify the process used in this study, a diagram was made. Figure 4 presents how the auxiliary methods required by this work are appended to the systematic process. The auxiliary actions, depicted on top level of diagram, are to be mainly worked as part of the embodiment design and detail design phases, although they are considered as early as possible in the process (dashed line).

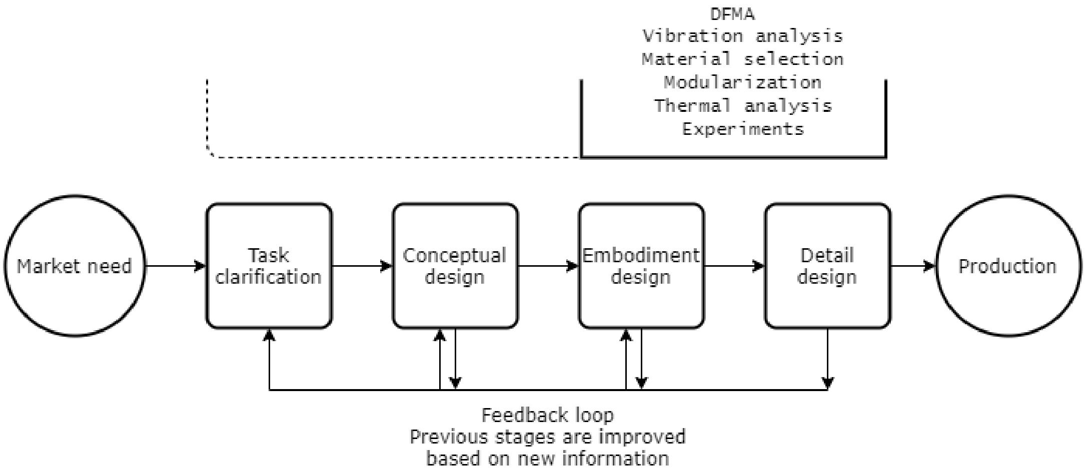


Figure 4. Diagram of design process and other methods used in this study (Mod. Pahl & Beitz 2007, p. 130)

2.2.1 Task clarification

The purpose of task clarification is to find out what goals the solution to be designed needs to achieve. Desirable and non-desirable features are specified. Resulting document from task clarification is a requirement list. Entries in the requirement list are classified as demands or wishes. Demands are such requirement that must be fulfilled in any case. Wishes are considered when reasonable but might be disregarded due to, for example, costs or technical complexity. Wishes should be classified as major, medium or minor importance. Entries in the requirement list should be described qualitatively wherever applicable. If qualitative definition needs to be used, the definition must be as clear as possible. (Pahl & Beitz 2007, p. 145-147)

Requirement list of even simple systems can become long and if the list is unstructured, it is difficult to read. To improve readability, entries in the list can be divided into different categories, based on functions or subsystems for example.

Writing down the source of demand can be useful. When done, going back to the original author is possible. By interviewing the original author, the true goal behind the requirement can be found out and evaluation carried out whether changing it is feasible. (Pahl & Beitz 2007, p. 148)

In perfect situation, a requirement list should be finalized and locked down as it is first created. However, situation and goals may shift during the development process and any changed or added requirements must be updated to the original document. (Pahl & Beitz 2007, p. 153)

Success of the project can be determined by reflecting to the requirement list – if large percentage of requirements and wishes are fulfilled by the final product, the project is successful.

During the revision, and when creating the initial requirement list, a checklist of possible options can be used. The checklist, depicted in Table 1, allows not only to create a comprehensive starting point for the list but also makes it possible to divide the entries into structured categories. (Pahl & Beitz 2007, p. 151)

Most of the initially documented requirements are explicit and therefore easily translated into direct product parameters. A much larger challenge is introduced by implicit requirements, which are not necessarily expressed or documented but result in very negative impact for the customer if they are not fulfilled. (Pahl & Beitz 2007, p. 150)

Table 1. List of example headings for writing requirement list (Mod. Pahl & Beitz 2007, p. 149)

Main headings	**Examples**
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension
Kinematics	Type of motion, direction of motion, velocity, acceleration
Forces	Direction of force, magnitude of force, frequency, weight, load, deformation, stiffness, elasticity, inertia forces, resonance
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversion
Material	Flow and transport of materials, Physical and chemical properties of the initial and final product, auxiliary materials, prescribed materials (food regulations etc)
Signals	Inputs and outputs, form, display, control equipment
Safety	Direct safety systems, operational and environmental safety
Ergonomics	Man-machine relationship, type of operation, operating height, clarity of layout, sitting comfort, lightning, shape, compatibility
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances, wastage
Quality control	Possibilities of testing and measuring, application of special regulations and standards
Assembly	Special regulations, installation, siting, foundations
Transport	Limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of dispatch
Operation	Quietness, wear, special uses, marketing area, destination (for example sulphurous atmosphere, tropical conditions)
Maintenance	Servicing intervals (if any), inspection, exchange and repair, painting, cleaning
Recycling	Reuse, reprocessing, waste disposal, storage
Costs	Maximum permissible manufacturing costs, cost of tooling, investment and depreciation.
Schedules	End date of development, project planning and control, delivery date

The measurement system is work of a multidisciplinary team and therefore the requirement list must consider needs not only from mechanical point of view but also from electrical, automation, software and measurement departments. Therefore, it was chosen to hold meetings with respective personnel and compile requirements based on it.

2.2.2 Conceptual design

Conceptual design is a part of the design process during which essential problems are identified based on requirements, function structures are formed and working principles sought. Finally working principles are combined into working structure and principle solution to the problem is found. (Pahl & Beitz 2007, p.159)

When the goal is to find entirely new solution, solution principles or technologies based on old, traditional methods will most likely not yield the best results. Sometimes the designer might favor old conventions based on experience and disregard new ones, which may in fact turn out to be more techno-economically fit. To battle this problem, abstraction is used - any specific existing solutions are ignored, and only general, essential issue is focused on. Result of abstraction is crux of the task, which only includes essential function and constraints without biasing any particular solution. For example, when designing a pumping solution for process industry, the crux of the task might not necessarily be to design a centrifugal pump, but to come up with a way to transport slurry from place A to place B. This opens possibilities for non-traditional solutions, which might even remove the need to use any kind of pump. Turning a specific definition of a task into a general one is called broadening. (Pahl & Beitz 2007, p.161-162)

In order to proceed with next steps in conceptual design phase, the essential problem needs to be identified. A step-by-step abstraction method is proposed by Pahl & Beitz (2014, p. 164):

- “Step 1. Eliminate personal preferences.
- Step 2. Omit requirements that have no direct bearing on the function and the essential constraints.
- Step 3. Transform quantitative into qualitative data and reduce them to essential statements.
- Step 4. As far as it is purposeful, generalise the results of the previous step.
- Step 5. Formulate the problem in solution-neutral terms.”

According to the authors, the analysis results in general definition of the task “- without laying down any particular solution”. Once it is defined, overall function can be recognized and broken down into subfunctions. The resulting system is called function structure. It can be visualized using a block diagram which specifies input and output flows of energy, material and signals. When working on an original design, the basis of a function structure is requirement list. In case of adaptive design, function structure of a similar existing solution can be used as base. (Pahl & Beitz 2007, p. 165, 169-170)

Having defined the function structure, the designer must next find working principles to fulfill the subfunctions. The working principles are then combined into a working structure using morphological matrix. In this approach, the subfunctions are assigned as rows of the matrix and working principles as columns. Illustrations or text-based descriptions can be added to the cells. Compatible solutions can be combined and marked in the matrix, resulting in working structure. (Pahl & Beitz 2007, p. 181-182, 184)

In most cases there will be multiple possible approaches, resulting in many different variants. To properly choose the best option for further development, evaluation method is needed. Method, modified from the approach suggested by authors is as follows: Evaluation criteria is identified and weighed, values are assessed and summed. For effective comparison, the criteria are recommended to derive from headings depicted in Table 2. After overall value has been calculated, variants can be compared. (Pahl & Beitz 2007, p. 192-193)

Table 2. Basic headings for evaluating conceptual design variants (Mod. Pahl & Beitz 2007, p. 193)

Main headings	**Examples**
Function	Characteristics of essential auxiliary function carriers that follow out of necessity from the chosen solution principle or concept variant
Working principles	Characteristics of the selected principle or principles with respect to simple and clear-cut functioning, adequate effect, few disturbing factors
Embodiment	Small number of components, low complexity, low space requirement, no special problems with layout or form design
Safety	Preferential treatment of direct safety techniques (inherently safe), no additional safety measures needed, industrial and environmental safety guaranteed
Ergonomics	Satisfactory man-machine relationship, no strain or impairment of health, good aesthetics
Production	Few and established production methods, no expensive equipment, small number of simple components

Table 2 continues. Basic headings for evaluating conceptual design variants (Mod. Pahl & Beitz 2007, p. 193)

Quality control	Few checks and tests needed, simple and reliable procedures
Assembly	Easy, convenient, and quick, no special aids needed
Transport	Normal means of transport, no risks
Operation	Simple operation, long service life, low wear, easy and simple handling
Maintenance	Little and simple upkeep and cleaning, easy inspection, easy repair
Recycling	Easy recovery of parts, safe disposal
Costs	No special running of other associated costs, no scheduling risks

It must be kept in mind that evaluation does not yield the absolute truth, it is merely a tool to assist the designer to make the decision. Different uncertainty factors and information gaps can skew the results of the evaluation. (Pahl & Beitz 2007, p. 197)

Once the principle solution is selected, design can move into embodiment design phase.
The task that is handled during this thesis work is unclear whether it is original design or adaptive design, that could be based on existing technologies entirely. In purely adaptive designs, the conceptual phase could be ignored. Therefore, it is questionable if the conceptual design phase would be needed during this design task. In the end, it was decided to be included because it allows to create many possible routes and select the best from them systematically. If it were chosen to go straight to embodiment design, there is a possibility that some unconventional, perhaps better solutions overall would have been left undiscovered.

2.2.3 Embodiment design

During embodiment design, the chosen principle solution is refined so far that the final layout is achieved. In this phase, the overall system layout must be invented. The arrangement of components and spatial compatibility must be laid down. Form design will be done in general level: component shapes and materials are determined preliminarily. Production and assembly of system is considered and solutions to auxiliary functions must be found. (Pahl & Beitz 2007, p. 227)

According to Pahl & Beitz (2007, p.159), embodiment design differs from previous phase in such a way that:

- “It involves large number of corrective steps
- many actions are performed simultaneously
- several steps must be repeated at a higher level of information
- additions and alterations in one area have repercussions on the existing design in other areas.”

The general workflow for embodiment design starts by identifying requirements that have crucial bearing on embodiment, such as size-, or arrangement-determining requirements. Then, spatial constraints are determined. They can be restricting constraints such as clearances, installation requirements or limited dimensions. A rough layout is prepared based on crucial requirements and spatial constraints. It is done with focus being on main function carriers. The rough idea of the layout and form design can be made into a scale 3D model. The main result of this is one or more preliminary layouts. Preliminary layouts and form designs must now be developed further, to include solutions for all remaining function carriers and auxiliary functions. For auxiliary functions, known solutions such as standard parts and catalogue parts are recommended. When developed far enough, the variants are evaluated against technological and economic criteria. The overall layout is now fixed. Final step is to optimize and eliminate weak spots from the final layout. Errors can be identified based on evaluation scoring. Now the layout can be passed on to detail design. (Pahl & Beitz 2007, p. 228-231)

As mentioned before, embodiment design involves repeating actions. To systematically go through phases during design, a checklist (Table 3) is proposed by authors.

Table 3. Checklist to aid designer during embodiment design phase (Mod. Pahl & Beitz 2014, p. 234)

Headings	**Examples**
Function	Is the stipulated function fulfilled? What auxiliary functions are needed?
Working principles	Do the chosen working principles produce the desired effects and advantages? What disturbing factors may be expected?
Layout	Do the chosen overall layout, component shapes, materials and dimensions provide: Adequate durability (strength) Permissible deformation (stiffness) Adequate stability Freedom from resonance Unimpeded expansion Acceptable corrosion and wear with the stipulated service life and loads?
Safety	Have all the factors affecting then safety of components, of the function, of the operation and of the environment been taken into account?
Ergonomics	Have the human-machine relationships been taken into account? Have unnecessary human stress or injurious factors been avoided? Has attention been paid to aesthetics?
Production	Has there been technological and economic analysis of the production processes?
Quality control	Can the necessary checks be applied during and after production or at any other required time, and have they been specified?
Assembly	Can all the internal and external assembly processes be performed simply and in the correct order
Transport	Have the internal and external transport conditions and risks been examined and taken into account?
Operation	Have all the factors influencing the operation, such as noise, vibration, handling, etc. been considered?
Maintenance	Can maintenance, inspection and overhaul be easily performed and checked?
Recycling	Can the product be reused or recycled?
Costs	Have the stipulated cost limits been observed? Will additional operational or subsidiary costs arise?
Schedules	Can the delivery dates be met? Are there design modifications that might improve the delivery situation?

The list ensures that essential things are not forgotten and provides a mental stimulus to keep the factors in mind always while designing. Each item in the checklist should be examined step by step, regardless of its connections and similarities with other factors. (Pahl & Beitz 2007, p. 233)

To accompany the checklist, some basic rules are proposed. The rules, that apply for all embodiment designs are clarity, simplicity and safety. Clarity, in this context means clarity of design. Successful design choices are often clear and self-explanatory. Simple shapes and simple assemblies with low number of components generally bring economic advantage. Third rule, safety includes factors such as strength, stability, reliability and accident prevention. Protection of environment is part of safety. (Pahl & Beitz 2007, p. 234-235)

2.2.4 Detail design

During this part of design process, final choices regarding design are done in greatest detail. Part shapes, forms, manufacturing methods, materials and surface properties are defined. Production documentation – part manufacturing drawings, component lists and assembly drawings are prepared during this phase. (Pahl & Beitz 2007, p. 436)

2.2.5 Principles of modular product design

Modular products are machines, assemblies or components that fulfill their function as a combination of building blocks (modules). Modular systems are valid if some problem differs from case to case and different variants of same product would have to be provided. Clear benefits are gained if, for example, in all cases half of the product could be identical and only other half variated based on case. Production also benefits, as identical modules can be used for larger variety of systems, increasing batch sizes. (Pahl & Beitz 2007, p. 495, 508)

Modularity must be considered already in the beginning of development. In task clarification, investigation is needed to find out what module variants so demanded that they are reasonable to develop. Special care must be taken during building of function structure because it defines the layout of system quite rigidly. (Pahl & Beitz 2007, p. 500, 503)

In this study, the need for modularization comes from the need to work with different widths of conveyors and installation related problems: the device must scale across different width conveyors. Installation site related limitations requires the system to be transported in small and lightweight modules.

2.3 Material selection process

Material technology is constantly advancing, life cycle cost requirements and environmental aspects are becoming more and more demanding. This makes material selection quite a challenging task – controlled method (Figure 5) will be required.

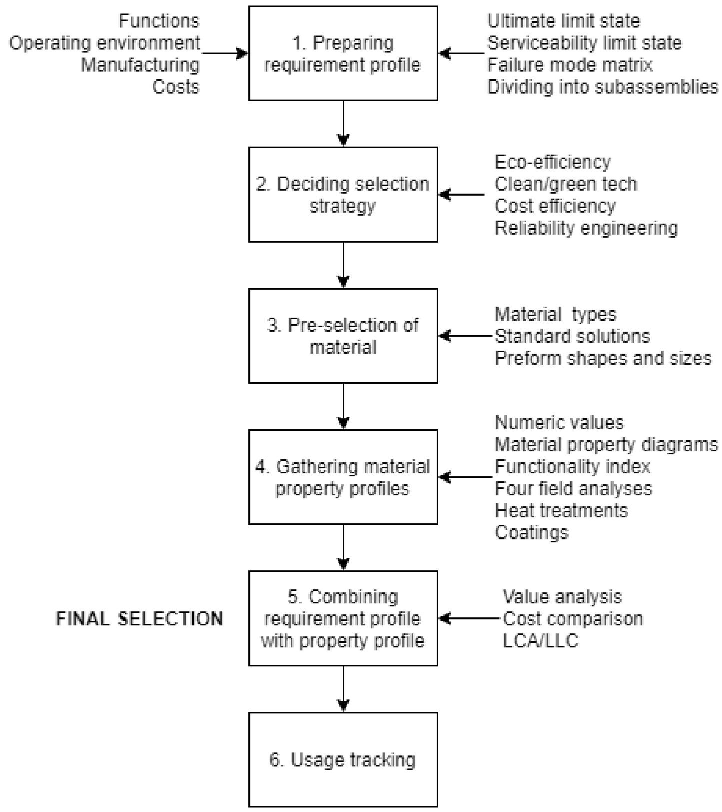


Figure 5. Schematic of systematic material selection process (Mod. Eskelinen & Karsikas 2013, p. 47)

Similar to product development process, this method also begins by compiling requirements. Four overlapping demand sections are considered: operating environment, functionality, manufacturing and costs. Operating environment introduces challenges such as wear, temperature and corrosion. Functionality includes functional requirements: carrying the weight and preventing deformation, absorbing energy. Manufacturing aspects such as weldability, castability and machinability are considered. Costs should be evaluated starting from purchase of material, manufacturing, inspection and usage, all the way up to recycling of product. Requirements need to be listed not just by environmental condition but in terms of needed material properties. The final material choice is a compromise between all the previously described aspects. (Eskelinen & Karsikas 2013, p. 47-48)

After requirements, a selection strategy is chosen. Depending on what the goal is, strategy might focus on cheap production cost and lower lifetime or higher initial cost but lower overall lifetime cost as the product life is longer. Nowadays popular, and even legally enforced choice is to focus on green or carbon neutral material choice, leading to more environmentally friendly product. Pre-selection is done to rule out any unlikely materials and focus search on more potential choices. For the potential materials, material property tables are gathered with all the attributes that requirement profile shows important. Different properties might be given a weight multiplier to emphasize the importance. Final material choice is done by selecting the material that fits the selection criteria best. (Eskelinen & Karsikas 2013, p. 48-50)

In this application, considerations need to be taken as the measurement system will be installed outside, possibly in corrosive environment. It will also need to be lightweight, stiff, and highly manufacturable.

2.4 Design for Manufacture and Assembly

Design for Manufacture and Assembly (DFMA) is a methodology that combines ease of manufacturing individual parts with efficient assembly operation to form the final product. The benefits of DFMA are, amongst others, lower manufacturing and assembly costs and overall simpler product structure. ReVelle (2002, p. 70) suggests following considerations to be taken during design:

1. “Simplicity
2. Standard materials and components
3. Standardized design of the product itself
4. Specify tolerances based on process capability
5. Use of the materials most processed
6. Collaboration with manufacturing personnel”

The first consideration, simplicity, includes multitude of concrete design actions: minimizing the number of parts, minimizing the use of fasteners and minimizing reorientations during assembly. Multifunctional parts and modular assemblies are encouraged. Steps 2 and 3 encourage to standardize materials, components and entire designs. Component and material-based standardization is useful inside company or specific to product family. Even designs of entire assemblies can be reused in other products, leading to time savings in whole design process. The author implies that the key point in introducing standardization is enforcing it and keeping related documentation available and up to date. (ReVelle 2002, p. 70-71)

Any tolerances specified should be according to what the used production process can handle. Many designers are tempted to mark too closely tolerated features where they are not even needed. To simplify manufacturing, using common materials is encouraged. Using materials that are already used elsewhere in company will ease the stress on inventory. Purchasing a preform that is as far processed as possible is better. (ReVelle 2002, p. 71)

For maximum manufacturing ease, collaboration with personnel is required. It is better to develop the design to be easy to fabricate and assemble from the beginning, than to realize the problems in later stage of product lifecycle. Things such as self-locating components and components that can be installed only one way make great relief for manufacturing process. Adjustments should be kept to minimum, the more adjustments there are the more manual work it requires to set them correct, also increasing the possibility for system to go out of adjustment with time. Special tooling should be avoided. Managing extra tools is a cost, similar to the cost that extra inventory items create. (ReVelle 2002, p. 72-73)

2.5 Experimental design

It was clear to the company that light has interfering effect on the laser scanners. Even ordinary lightning of an office or industrial hall was causing minor difficulties, not to mention powerful lightning that a color camera solution requires. There was not enough information on what kind of effects the properties of light and relative device locations have exactly.

Another problem is that when camera and light source are positioned closely and looking through a glass, the light tends to reflect to the camera rendering it partially blind. An experiment is made in order to find out what is the most compact setup to position the equipment without blinding the camera. It was decided to do two simple experiments to solve the issue. Gathered data is valuable to properly position instruments in the chip scanner in optimal way, and generally applicable in other scanner types as well.

According to MoreSteam (N.d.) the term experiment is a "systematic procedure carried out under controlled conditions in order to discover an unknown effect – ". In addition to unknown effects, experiments can be used as a tool to illustrate a known effect or confirm a hypothesis. The act of planning and preparing experiment to gain optimal results is called experimental design. (MoreSteam n.d.)

Planning experimental procedure is a time-consuming process. To save time, the experimenter might feel tempted to start testing before a proper plan is made. There is no guarantee of accuracy, reliability, or validity of improperly planned research. To aid planning, Dean et. al. (2017, p. 7-12) propose a checklist for preparing experiments:

- "Define the objectives of the experiment
- Identify all sources of variation
    - Treatment factors
    - Experimental units
    - Blocking factors, noise factors, and covariates
- Choose a rule for assigning the experimental units to the treatments
- Specify the measurements to be made, the experimental procedure, and the anticipated difficulties
- Run a pilot experiment
- Specify the model
- Outline the analysis
- Calculate the number of observations that need to be taken"

The term treatment factor is defined as a variable the effect of which on the data is to be studied. Experimental unit is the target of treatment. For example, in a medical experiment, the treatment factors could be the type and dosage of medical substance and experimental unit some defined group of people. (Dean et. al. 2017, p. 8-9)

Testing plans in this study are made specifically to serve the purpose of this particular design and not generally applicable. Therefore, the tests were designed to be as simple and as quick to perform as possible.

2.5.1 Laser interference

Objective of the experiment in this case is to find out how type and arrangement of light affect the laser-based measurement. It is known that a dim light will not cause harm to measurement, but it makes color imaging impossible. One of the factors affecting depth of field is aperture: with low aperture depth of field is largest. In order to use low aperture, light level must be high. On the other hand, laser visibility will suffer from bright ambient light. Thus, balance must be found so that there is enough light for color cameras, but light must be positioned so that any other measurement instruments are not affected.

Based on the second step in the checklist, it was decided that tests will be made in completely dark environment, to eliminate any effect of possible changing light conditions. Only light sources in the room are light for color camera and laser source of a certain 3D scanner. To make the test more realistic, a glass would be added through which the laser scanner and camera would be looking through. Experimental setup is depicted in Figure 6, where the laser fan is highlighted with red and light beam with blue. The calibration object is a 100 x 100 mm rectangular hollow section (RHS). Glass is a 4 mm thick low-iron glass.

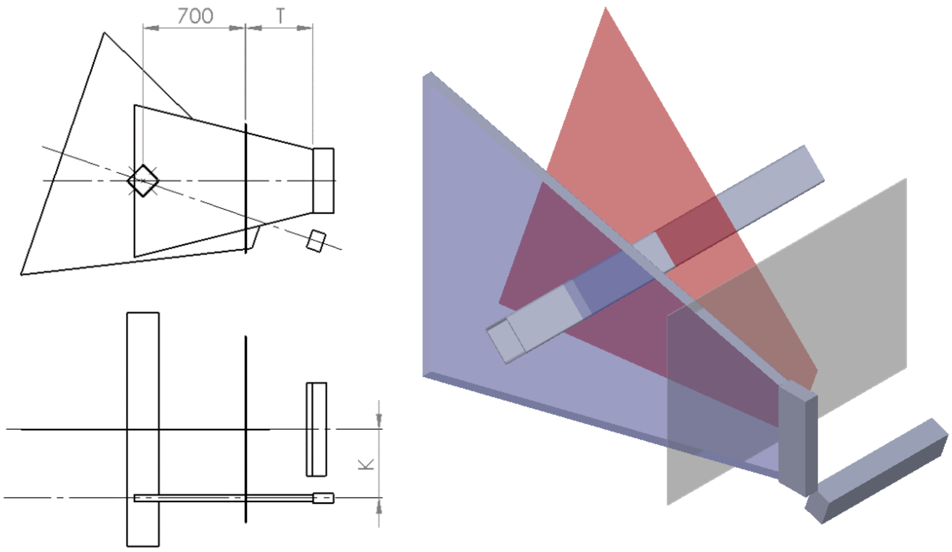


Figure 6. Calibration piece, glass, laser scanner and light arrangement for laser interference experiment

Chosen treatment factors and their value variations are described in Table 4. Measurements are made to evaluate the accuracy of laser scanner. It is evaluated by scanning a calibration object. Inaccuracy in dimension and mistakes in point cloud are assessed. The results are to be determined qualitatively. Only observational unit is accuracy of laser scanner. In this study, one observation will be recorded for each permutation. It is believed that the results will carry unchanged to the actual application as identical glass, laser scanner and light is used.

Table 4. List of treatment factors and related variations in laser interference test

Treatment factor	**Variations**
Type of light	conventional LED line light collimated LED line light
Distance from laser to glass (*T*)	100 or 200 mm
Lateral distance between light and laser line (*K*)	50 mm – 400 mm in 50 mm increments

2.5.2 Camera interference

The aim of this experiment is to find optimal positioning for camera and light looking through glass so that the light does not reflect into the camera and blind it. Limited space inside scanner acts as motivation. Setting the camera and light into different planes would solve the issue but results in variating brightness as the object’s distance from the camera changes. Consistent lightning is required for accurate measurement and thus the equipment will be set into same plane.

A line camera and collimated LED light were set into a test bench and data from camera was captured. The test setup is depicted in Figure 7. The positioning and angles were chosen so that they are close to what the setup will be in final scanner.

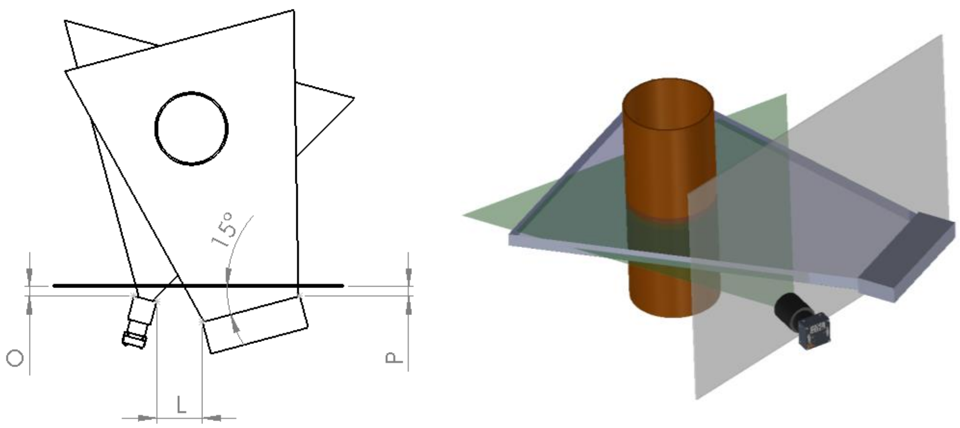


Figure 7. Test object, camera and light arrangement for camera interference experiment

Room condition was identical to laser experiment. Chosen treatment factors are listed in Table 5. Exposure time of 1000 µs is used. Data from the camera is captured and analyzed qualitatively. The image quality of the target object, 200 mm PVC tube is not important in this case. Focus will be instead on interference which is visible as a clear white artifact in the image. Evaluation is done based on percentage of image that is covered by artifact.

Table 5. Treatment factors and variations in color camera interference test

Treatment factor	**Variations**
Distance from camera to glass (*O*)	25 or 10 mm
Distance from LED to glass (*P*)	25 mm
Lateral distance between light and camera (*L*)	50 mm – 200 mm in 50 mm increments

2.6 Vibration isolation

The vibrations in linear systems can be divided to two categories: forced and free. Free vibrating systems vibrate without any external forces. Forced vibrations occur due to excitation of external forces. The frequency of excitation is independent of the natural frequency of the system, and resonance occurs when the excitation frequency coincides with natural frequency of the system. Damping is the effect where the vibration energy in system is dissipated through friction, heat losses and other resistances. A damped free vibration will die out as time passes. (Norton & Karczub 2003, p. 2)

The goal is to isolate the wood chip scanner from the vibration created by machinery operating nearby. Simplified approach is to divide the situation into parts: source, path, and receiver of vibration. By altering one or more of those, the vibration experienced by receiver can be weakened. Altering the surrounding machinery is difficult, as the type, power, location and frequencies of the machines are unknown. The path of vibration, frames and foundations of conveyors, is also difficult to modify. However, it is possible in some cases to locate the scanner as far away from the sources as possible.

The universal solution in this case, is to modify the natural frequency (ω_n) of the sensitive system to be in such a regime that diminishes resonance. The fraction of excitation force that transverses into receiver can be expressed with transmissibility. The curves representing the relationship between frequency ratio ω/ω_n, damping ratio ζ and transmissibility are depicted in Figure 8. (Norton & Karczub 2003, p. 323)

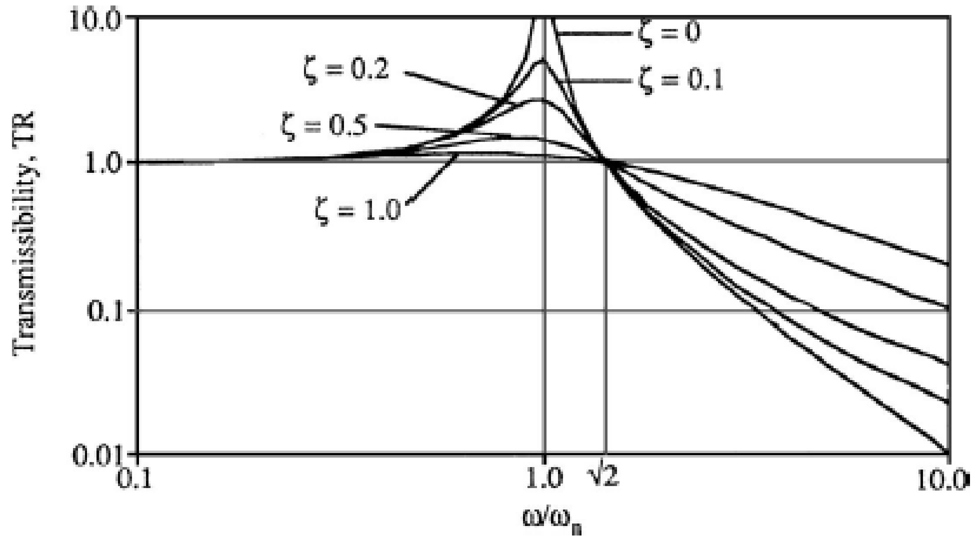


Figure 8. Transmissibility - frequency ratio graph for different damping ratios (Norton & Karczub 2003, p. 323)

The curves coincide at the frequency ratio of √2, when increasing the frequency ratio beyond this point, the transmissibility is less than 1 and isolation occurs. If frequency ratio is less than √2, system is at the resonant regime and vibration amplification occurs. In highly damped system, the effect of high frequency ratio is less powerful. (Norton & Karczub 2003, p. 323)

System natural frequency can be altered by tuning system mass and using anti-vibration mounts. The selection of anti-vibration mounts (stiffness of mount) should be done so that lowest possible natural frequency is found. Manufacturer datasheets are used to find the natural frequency. (AMC Mecanocaucho n.d. p. 11)

2.7 Thermal analysis

It is required to maintain constant temperature of 20 °C inside the measurement device. In order to manage this, thermal analysis is needed. Required wall thicknesses, insulation materials and heating or cooling device power will be specified based on the analysis.

The definition of cooling load is the amount of heat that must be removed from the room in order to maintain a constant temperature. Heating load is defined similarly. Only the heat energy flow direction is opposite. There are three modes of heat transfer conduction, convection and radiation. (Spitler 2009, p. 5)

Heat flows through the roof and walls of structure are generally considered conduction. Steady state conduction heat transfer through a wall, as described by Spitler (2009, p. 6), is described as:

$$q = A\frac{(t_1 - t_2)}{R} \tag{2}$$

Where A is area of surface, t_1 and t_2 are temperatures in opposite sides of the surface. R is unit thermal resistance. If the wall consists of two or more layers, the unit thermal resistances of each layer can be simply summed together. (Spitler 2009, p. 6)

Thermal mass is a property of structure that allows it to store thermal energy. It works as a buffer, dampening the effects of large variation in outside temperature. When outside temperature is high, the mass absorbs the energy, whereas when the temperature is low it will release energy to the surroundings, resulting in dampening effect. (The Concrete Centre n.d.)

Spitler (2009) implies, that because of effect of thermal storage and large variations in outside thermal loads the steady-state calculation method described in previous paragraph would not be valid. Two methods, a quasi-steady-state method and transient method, were compared. The quasi-steady-state method ignores thermal storage effect, whereas the transient method considers it. Two effects are noted: in transient method peak heat gain occurs later and its magnitude is 30% lower. (Spitler 2009, p. 9-10)

Quasi-steady-state calculation method was chosen because the structure studied in this thesis has relatively low thermal mass and complexity of transient calculation method is too high compared to the benefit it provides. Slight overdimensioning is considered acceptable since the overall cooling load is estimated to be low (< 2 kW). The chosen method results in conservative value of cooling power.

Two other heat transfer modes, convection and radiation can be combined into a single surface conductance to simplify the calculation procedure (Spitler 2009, p. 14). Sol-air temperature, a fictious temperature, is introduced. It represents a temperature that without any radiation or convection, gives same amount of heat entry through surface that would happen with all different components of radiation and convection (Al-Saud 2009, p. 2). It is formulated as

$$t_e = t_o + \frac{\alpha I_t}{h_o} - \varepsilon \delta R / h_o, \tag{3}$$

where ε is hemispherical emittance, t_o outdoor temp, δR the difference between long wave radiation incident on surface from sky and surroundings and radiation emitted by black body at outdoor air temperature. α is absorptance of surface for solar radiation, I_t total solar radiation incident on surface and h_o the coefficient of heat transfer by long wave radiation and convection and outer surface. (Al-Saud 2009, p. 2)

A value of 250 W/m^2 is used for I_t as it is mean value for possible installation locations. Al-Saud (2009) suggests the value for last term to be 4 °C for horizontal surfaces and 0 °C for vertical. The term α/h_o is 0,026 for light colors and 0,052 for dark colors.

The total cooling load can be calculated by formulating a heat balance equation of the previously mentioned factors. Heating load is calculated similarly, just the direction of heat transfer is inverted. Module dimensions and materials were changing throughout the process;

therefore, a spreadsheet solution was required for easy modification of values. Thermal calculations were done using Excel.

2.8 Ingress protection

European standard EN 60529:1992 describes enclosure classification of electric devices. The purpose is to classify levels of protection against human accessing dangerous parts inside enclosure and infiltration of foreign matter such as dust and water. (SFS-EN 60529 2019, p. 63)

In this application, ingress protection (IP) classification is needed because the measurement device needs to be protected. The system will contain high-voltage components and sensitive measurement instruments – protection is required even by law.

IP classifications are rated with two classification numbers and up to two complementary letters (Figure 9). First number defines enclosure protection against foreign objects and dust. Second number defines protection from water. Higher number represents better protection. Additional letters may be used to specify for example high voltage or are the moving parts of the device operational or stationary during testing. (SFS-EN 60529 2019, p. 67)

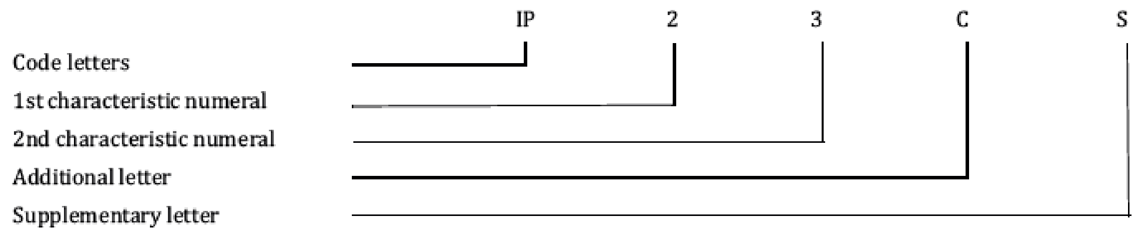


Figure 9. Ingress protection code markup structure (SFS-EN 60529 2019, p.66)

The definitions of each class are described in standard. It also specifies the methods to use when testing protection level. Temperature, moisture, and other properties of the testing space are determined. The testing that is done for solid foreign objects is done using special testing tools, to represent a human finger or hand. All test tool materials, dimensions and testing forces are specified. (SFS-EN 60529 2019, p. 70)

Dust-related tests are done with talcum dust. A suction pump is used to create pressure that is below atmospheric pressure to the enclosure. Dust infiltration is easily seen. Water tests are done with equipment that simulates rain or more powerful sprays. (SFS-EN 60529 2019, p. 79, 81)

In any case, all test procedures are well documented to ensure accurate classification. The protection class requirements and tests that the chip scanner must comply will be done according to method described above.

3 RESULTS

The resulting design is described in this chapter. Requirement specification and choice of concept is covered first. Finally, results of supporting methods, embodiment phase and complete design are introduced.

3.1 Requirement specification

Requirements list was gathered based on discussion held with experts of different fields. Based on visit on possible installation sites, the location was found to be difficult. Conveyors can reach high altitudes and be covered closely by walls and ceiling. The path leading to a viable installation spot can consist of narrow passageways, doors and stairs. Therefore, a requirement for modular structure was introduced. Compact and lightweight modules could be transported to site easily without dismantling walls or roofs. A maximum mass carriable by 2 persons is specified in standard ISO 11228. Handles will be fitted for lifting and carrying modules. A requirement of installation without hot work was also listed because not many mills allow doing hot work.

DFMA related ordinary requirements such as easy fabrication and straightforward assembly are not listed, as they are obvious. However, wishes were written down to have as much of the product manufactured in-house as possible. For material selection, the selection strategy is specified but not locked to any material at this point. Environmental factors – vibration, dirt, temperature and ingress protection demands are listed in their own section.

Laser safety requirements, such as viewing protection, interlocking and key switch operation were added based on standard IEC 60825. The ingress protection will be designed based on SFS-EN 60529. In section 4, the demand for minimum size of electrical enclosures is listed. At this stage, the true list of components inside scanner cannot be determined. However, some initial guess is needed to carry on design of mechanical structure. An estimate based on enclosure size of similar scanner was used.

The belt conveyor commonly used in transport of wood chips is based on rubber belt and steel idle rollers. A lot of components in the belt system are wearing parts and require maintenance and replacements from time to time. The belt itself can last several years when used properly but the steel idle rollers are prone to wear and are replaced quite frequently, leading to an entry in list of demands.

Resulting requirement list is depicted in Table 6. The list is divided into categories based on functions. Any changes are kept track of by logging the date.

Table 6. Requirement list of chip scanner

	Requirements list **Chip Scanner 1**	Initial version 23.9.2019 Updated 2.4.2020
Changes	Demand/Wish	Requirement
		1. **Installation, transport, outer dimensions**
	D	Installable to conveyors specified in drawing CS1-00-00-801 Ability to fit to both conveyor designs with minor modification
	D	Installation without doing hot work
4.1.2020	D	System must consist of modules that fit through a 700mm wide door
4.1.2020	D	Maximum mass of one module is 50 kg
4.1.2020	D	Max width of total system in installation site: 1670 mm Max height of total system in installation site: 2000 mm
	D	Location and alignment tolerance build up after installation: X: 2 mm (0,5 degrees rotation) Y: 2 mm (0,5 degrees rotation)
	D	Modules fitted with removable lifting eyes and carrying handles
		2. **Environment factors**
	D	Ambient vibration isolation
	D	Temperature inside device is regulated to 20 °C. Outside temperatures ranging from –50°C to + 50 °C
	D	Dust and water proofing to spec IP54
		3. Mechanical specifications
	D	Device must have window(s) through which laser and color camera measurement is done. Must work even in dirty environment
	D	Device must have hatch/door for maintenance work
	D	Door/hatch equipped with non-locking safety switch
	D	Door equipped with heavy duty latch.
	W	Doors and latches must withstand abuse
7.1.2020	D	Laser safety compliant according to standard IEC 60825
	W	If equipped with washing fluid, it must be refillable without opening latches and interrupting measurement

Table 6 continues. Requirement list of chip scanner

2.4.2020	W	Manufacturable mostly using in-house production equipment
2.4.2020	W	Highly available, recyclable and low-cost materials
		4. Electrical and device specifications
	D	Color imaging and 3D scanning according to following: • Must be able measure all possible chip flows on conveyor • If 2 directions, both cameras should see common area • Color and laser must scan common area • Resolution and scan frequency as high as possible
	W	Laser equipped with tracheid detection
	W	Lining work of 3D cameras effortless
	D	Light for camera does not affect laser measurement
4.3.2020	D	Main electrical enclosure minimum size: 600 x 800 x 300 mm
	D	Electrical interface enclosure on outside of device. Minimum size: 380 x 300 x 155 mm
	D	Red beacons visible in all directions
	D	Buttons outside for opening door and resetting safety
	D	Inside light
	D	Grounding of all metal components
	D	Cable routings with wire shelf or equivalent based on electric drawing
	D	Temperature sensors in all modules
4.3.2020	D	Key switch for activating laser
		5. Maintenance
10.12.2019	D	Replacing key components must be possible under 15 minutes: • Cameras & scanners • Any component in electrical enclosure
	D	Maintenance of chip conveyor components must be possible without removing scanner: • Replacing belt • Replacing rollers

3.2 Concept

At this point we have clear understanding of what the product must achieve. The upcoming chapters present the intermediate results of conceptual design and the final choice of concept.

3.2.1 Crux of the task and abstraction

When designer works on this subject for the first time, the crux of the task might turn out to be “to measure wood chips on conveyor using laser scanners and color cameras”. However, that kind of approach is incorrect because it limits the solutions to choose from. A step-by-step abstraction was done to find the crux of the task. Result is as follows:

Step 1:

- Modular system
- 50kg, fit through 700 mm wide door
- Max dimension of assembled system: width 1670 mm, height 2000 mm
- Installation without doing hot work
- Constant temperature inside machine
- IP54
- Vibration isolation
- Measurement works in dirty environment
- Laser safety according to IEC 60825
- Measurement of volume
- Measurement of chip size
- Measurement of quality
- Electrical enclosures sizes: 600 x 800 x 300 mm and 380 x 300 x 155 mm
- Maintenance of scanner convenient
- Scanner does not bother maintenance of chip conveyor

Step 2:

- Modular system
- 50kg, fit through 700 mm wide door
- Max dimension of assembled system: width 1670 mm, height 2000 mm
- Constant temperature inside machine
- Vibration isolation
- Measurement works in dirty environment
- Measurement of volume, chip size and quality

Step 3:

- Modules carriable by 2 people, fit through common passages and doors
- Assembled system fits well to the installation site
- Constant temperature inside machine
- Vibration isolation
- Measurement works in dirty environment
- Measurement of volume, chip size and quality

Step 4:

- Modules carriable by 2 people and compact enough to fit all stages of transportation
- Independent on the environmental circumstances
- Measurement of volume, chip size and quality

Step 5: (Problem formulation)

- Measure volume, chip size and quality of wood chips independently of any environmental variables with system that is compact and lightweight

The definition described in Step 5 is the crux of the task. Next step in the process is to list overall function and break it down into subfunctions. Overall function is depicted as a diagram in Figure 10.

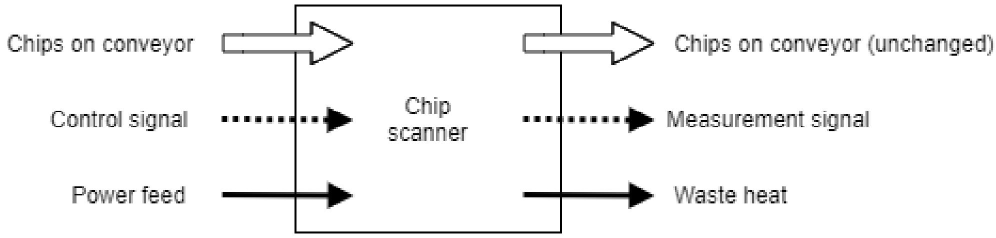


Figure 10. Overall function diagram of scanner

As an example, the overall function, measuring the wood chips, can be broken down into subfunctions based on what properties are measured. Those, along with other subfunctions were drawn into diagram presented in Figure 11.

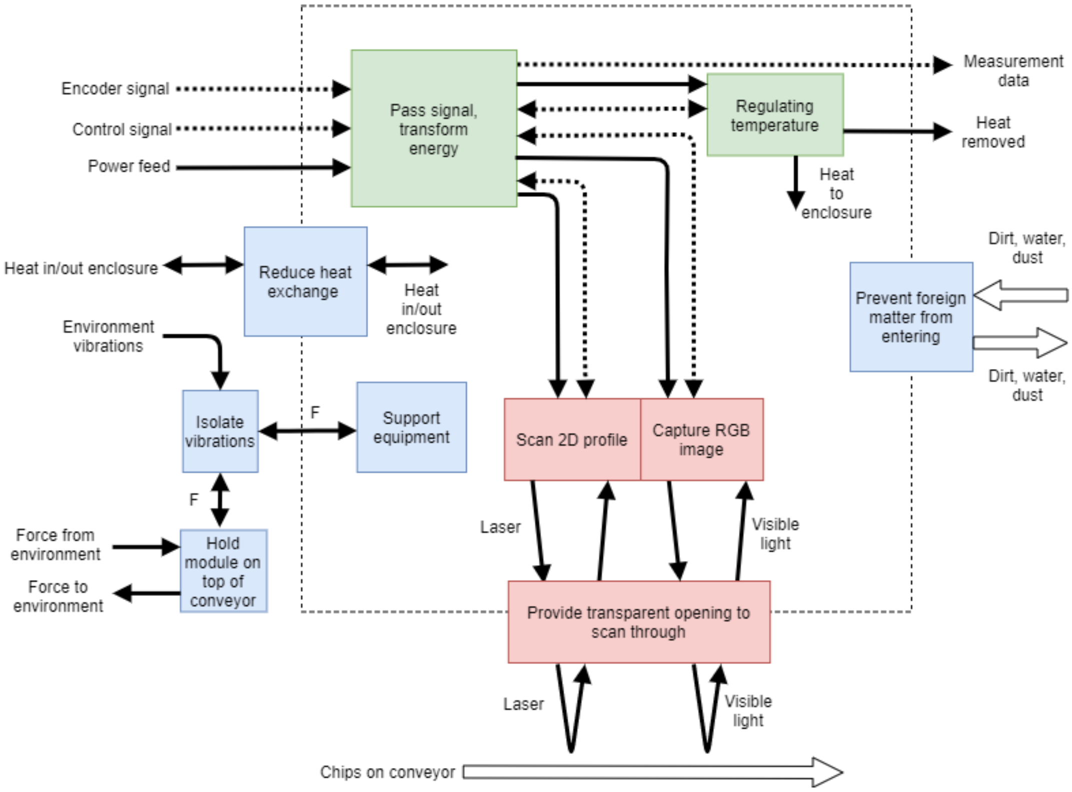


Figure 11. Detailed diagram of material, signal, and energy flows of system. Blue color represents common functions, red color scanning functions and green supporting functions.

The boundary between scanner enclosure and environment is marked with dashed line border. Any functions that work in the boundary area, such as reducing heat exchange and preventing foreign matter entrance, overlap the dashed line. Overall function is measuring woodchips. At this stage, subfunctions were divided into possible module groups: scanning functions (red), common functions (blue) and supporting functions (green). All subfunctions are as follows:

Scanning functions:

- 2D scanning
- Color imaging
    - Illumination
    - Capturing image

- Providing transparent opening to scan through
    - Thermal isolation
    - Dirt prevention

Supporting functions:

- Regulating temperature
    - Sensing temperature
    - Cooling
    - Heating
- Passing signals and transforming energy (main electrical enclosure)

Common functions for all modules:

- Preventing foreign matter from entering
- Reducing heat exchange through walls
- Supporting equipment
    - Measurement instruments
    - Cables
    - Auxiliary devices
- Holding module on top of conveyor
- Isolating from vibrations

3.2.2 Working principles and morphological matrix

All the subfunctions were arranged into morphological matrix (Table 7) rows. Different possible working principles were assigned as columns. For most functions, working functions existed already so no original development is needed.

For 2D scanning, the most common solution in the market is line laser, but also multi-point scanners exist. Color imaging choices are based on available sensor shape and technology, which is described in more detail in chapter 2.1.2. The available light sources for camera use nowadays are mostly LED but also diode lasers are used in some special cases. For this study only LED-based are considered. Lights shaped oblong, line and round are used for different applications.

There has been earlier research by the company on windows and glass cleaning system, so a natural action is to take that system as one of the options for aperture. Another option is to use a bare glass without wiper.

Vibration isolation theory is covered in chapter 2.6. Based on that, it was decided to rule out any other means but passive and active isolators. Also, mass tuning – modifying the vibration receiver's mass to enhance isolation can be used.

For framing, shell and insulation, the selection is done based on material and preform type. Aluminum extrusion and different steel hollow sections are options for frames. Steel, aluminum, fiberglass, and polymer materials are considered for outer shell. Solid preform insulation materials of glass wool and mineral wool are available for selection. Polyurethane is also available; it can be procured either in solid or sprayable form.

Finding different function carriers for heating was difficult, with only electric heating being viable. For cooling on the other hand, ventilation, heat pump air conditioning and thermoelectric cooling can be used.

Table 7. Morphological matrix for combining functions with solutions. Red color means scanning functions, blue common functions, green supporting functions.

Solutions / Sub-functions	1	2	3	4
2D scanning	Multi-point laser	Line laser		
Capturing color image	Line CMOS camera	Matrix CMOS camera	Line CCD camera	Matrix CCD camera
Illumination	Collimated LED	Traditional LED	Spotlight LED	
Providing transparent opening to scan through	Glass	Glass with wiper	Multi-layer glass	

Table 7 continues. Morphological matrix for combining functions with solutions. Red color means scanning functions, blue common functions, green supporting functions.

Vibration isolation	Passive	Active	Mass tuning	
Preventing foreign matter entrance	Steel shell	Fiberglass shell	Polymer shell	Aluminum shell
Reducing heat exchange through walls	Solid PU insulation	Glass wool insulation	Mineral wool insulation	Sprayable PU
Supporting equipment	Aluminum profile frame	Steel RHS frame	Steel CHS frame	
Holding scanner on top of conveyor	Aluminum profile stand	RHS welded stand		
Cooling	Ventilation	Heat pump	Thermoelectric cooler	
Heating	Electric heater			
Passing signals and transforming energy	Centralized	Decentralized		

3.2.3 Evaluating concept variants

Countless possible combinations can be formed but, in this case, only three potential ones were chosen for further inspection. They are deliberately chosen to represent different cost ranges, from cheap and simple, to delicate and costly. Variants are depicted in Table 8.

Table 8. Properties of conceptual design variants

Variant 1	**Variant 2**	**Variant 3**
- Multipoint laser - Matrix CMOS - Traditional LED - Glass - Passive vibration isolation - Steel shell - Glass wool insulation - Steel CHS frame - RHS stand - Ventilation - Electric heater - Centralized control	- Line laser - Line CMOS - Collimated LED - Glass with wiper - Passive vibration isolation - Steel/fiberglass shell - Sprayed PU insulation - Aluminum profile frame - RHS stand - Heat pump - Electric heater - Centralized control	- Line laser - Line CMOS - Collimated LED - Glass with wiper, multi-layer - Active vibration isolation - Fiberglass shell - Sprayed PU insulation - Aluminum profile frame - Aluminum profile stand - Heat pump - Electric heater - Decentralized control

To evaluate the variants, criteria was derived based on headings in Table 2. Technical criteria and scoring for different variants are listed in Table 9. Variants are scored from 0 to 5. Higher score means better performance at related criteria. Technical rating R_t and economic rating R_e are calculated by dividing total score with maximum possible total score. Economic criteria and scoring are listed in Table 10.

Table 9. Technical evaluation table for concept variants

Variants / Criteria	**Variant 1**	**Variant 2**	**Variant 3**
Functionality	2	4	5
Manufacturing, assembly, quality control	3	4	3
Transport & installation	3	4	5
Maintenance	2	3	3
Recycling	4	3	2
Total	14	18	18
Technical rating R_t	0.56	0.72	0.72

Table 10. Economic evaluation table for concept variants

Variants / Criteria	**Variant 1**	**Variant 2**	**Variant 3**
Material cost	5	4	3
Component cost	4	3	2
Manufacturing costs	5	3	2
Assembly costs	2	3	3
Possibility for in-house manufacture	5	5	5
Total	21	18	15
Economic rating R_e	0.84	0.72	0.6

The economic rating of variant 1 is the best but technical rating low. On the other hand, variant 3 is technically superior but lacks economic viability. The variant that has highest combined rating (R_t + R_e) is variant 2 and will be chosen for development. This variant is also balanced in terms of material selection: it uses steel for stiffness and fiberglass where light weight is needed. Both materials are low cost and easily available, which goes well with the requirement list.

3.3 Selection of measurement instruments

Based on factors described in Chapter 2.1.1, the laser scanner unit was chosen. Comparison for scanner models is listed in Table 11.

Table 11. Laser scanner selection criteria and comparison (LMI n.d.-a, LMI n.d.-b, Keyence n.d.)

	Scanner 1	**Scanner 2**	**Scanner 3**
Datapoint count per scan	1920	1280	3200
Resolution Z [mm]	0.07	0.092	Not listed
Resolution X [mm]	0.25	0.375	Not listed
CD [mm]	350	350	580
MR [mm]	1525	800	800
FOV [mm]	390 - 2000	390 - 1260	300 - 720
Scan rate [Hz]	370 – 5000	380 – 2500	Not listed

Scanner 1 was chosen. The measurement geometry is a perfect match for this conveyor shape and dimensions. The scanning area is configurable and when setup for this conveyor, the scan rate is more than 1 kHz. The precision at this range is satisfactory.

For line scan camera, all manufacturers deliver roughly the same specs. A camera with sensor resolution of 4096 x 2 and maximum line rate of 13 kHz is selected. Objective was selected so that it provides imaging area that matches with that of laser. Lens with focal length of 25 mm will provide 60-degree angle of view. The depth of field calculated for this set of optics is 327 mm, which is enough for staying in focus despite variating thickness of chip pile.

The selected collimated LED light has adjustable brightness without using a separate control unit, which stands out from the competing models. Brightness can be adjusted using a simple analog output. High linearity, lifetime and compact dimensions led to choosing this model.

3.4 Laser interference test

Test was successful and key factors for avoiding interference were found. The experiment setup is described in chapter 2.5.1. Experiment log and data is listed in appendix I and II. Figure 12 shows the data in visual form: green color meaning excellent data and red unusable data.

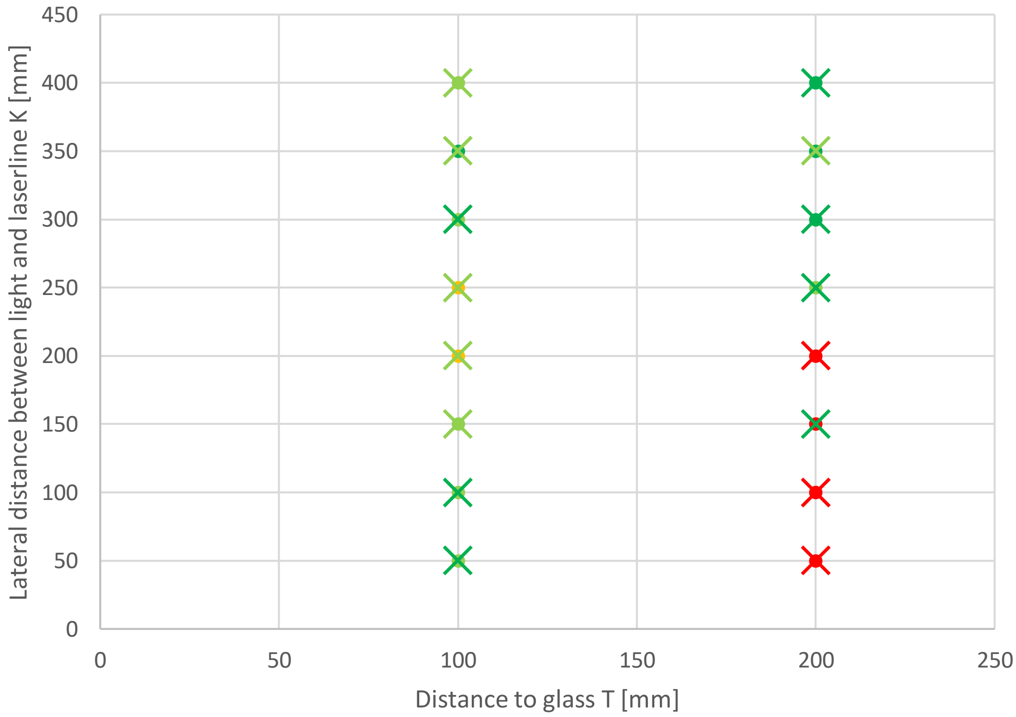


Figure 12. The effect of light positioning to laser data quality. Green means fine data, red poor quality.

Data points from collimated LED are plotted with marker X and points from ordinary light with marker O. Data quality was evaluated in scale from 0 to 5 with 5 being the best quality. The plot shows that moving the setup closer to the glass improves the situation regardless of light type. Moving the light laterally away from the laser line seems to improve the quality but this effect is nonexistent when distance to the glass is short. As conclusion, the best data can be achieved when positioning the light near the glass and as far away from the laser line as possible. Collimated light allows for slightly better overall result.

3.5 Camera reflection test

Testing log is presented in Table 12. Contradictory to the testing plan, in test case 013 a glare cover was used for the camera objective. Moving camera closer to the glass yields better results. The glare cover improves the results further: when comparing cases 011 and 013, the interference is reduced from 12% to 0% only by adding the cover. Conclusion is that the most compact setup (underlined) can be done by having the camera close to the glass with glare cover.

Table 12. Results of camera reflection test

Case number	**Lateral distance between light and camera L [mm]**	**Distance from camera to glass O [mm]**	**Distance from LED to glass P [mm]**	**Glare cover**	**Interference percentage**
001	100	25	25	No	6
002	70	25	25	No	20
003	120	25	25	No	5
004	160	25	25	No	0
011	50	10	25	No	12
012	70	10	25	No	4
<u>013</u>	<u>50</u>	<u>10</u>	<u>25</u>	<u>Yes</u>	<u>0</u>

3.6 Vibration measurement

To find out the vibration frequency spectrum in the installation site, measurements are needed. Measurements are done by logging smartphone accelerometer sensor data. Datasets of 120 seconds were taken when the chip conveyor was running at production speed and load. Measurements were taken at two potential installation locations in the conveyor frame. The measurement locations and related coordinate systems are presented in Figure 13.

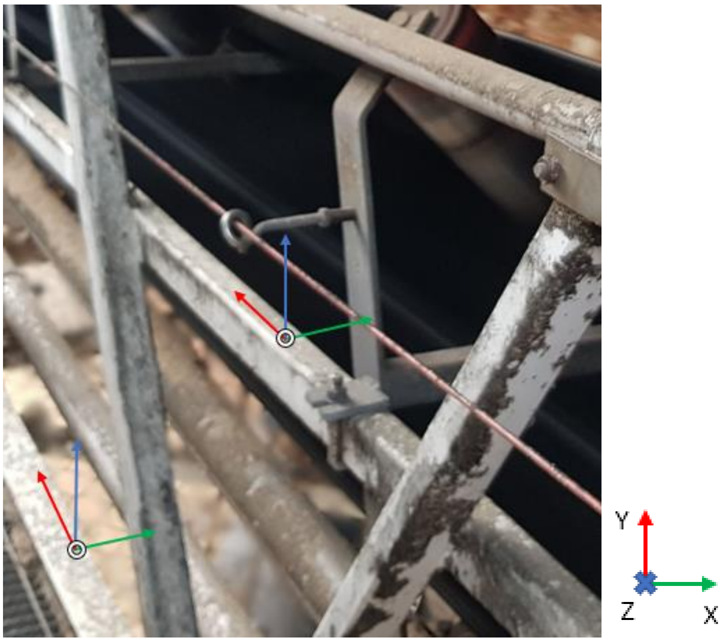


Figure 13. Vibration measurement locations and related coordinate system in conveyor frame

3.7 Vibration analysis

Measured vibration data is depicted in Figure 14. The bottom measurement location is covered in right side plot, the data recorded from top beam is left side. Power spectral density (PSD) is used to represent how energetic vibration is.

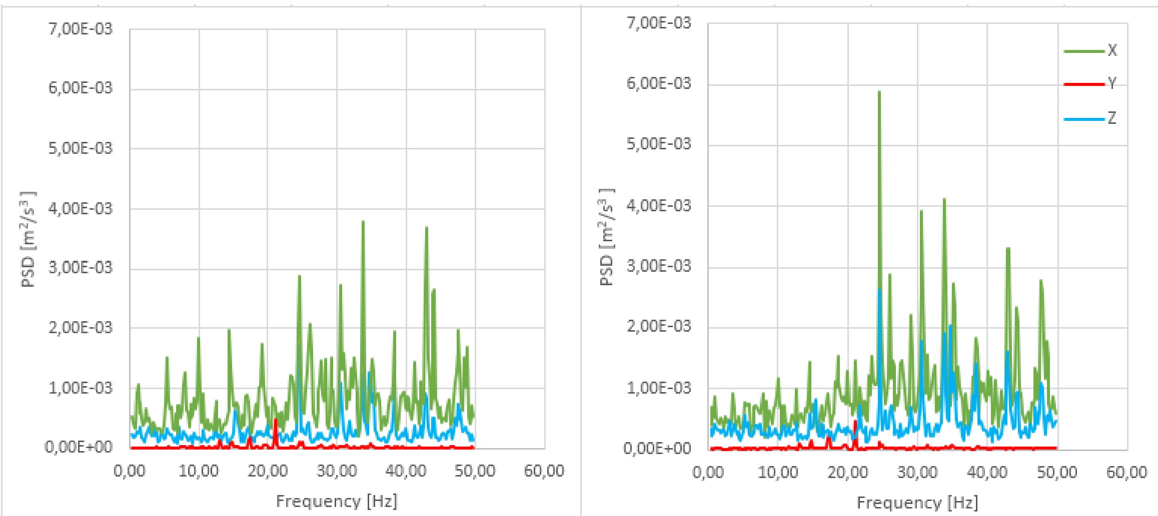


Figure 14. Vibration power spectral density versus frequency graphs for two different measurement locations

Vibrations in Y-axis are almost nonexistent, whereas on X-axis the power is highest. Even there, vibrations are weak, with maximum acceleration in whole dataset being less than 0,05 g. Both measurements show that frequencies above 24 Hz feature the most energetic vibrations. Frequencies under that are neglected because they are so weak. Selection of the anti-vibration mount is done based on the lowest excitation frequency of 24 Hz.

Manufacturer provides graphs (Appendix III and IV) that can be used to calculate the natural frequency of system and deflection based on type of anti-vibration mount and mass. In initial calculations, scanner mass was estimated, and refined calculations were made as design was mature enough. Anti-vibration mount was selected so that resulting natural frequency becomes as low as possible with scanner mass.

The selected mount (BRB 70-50) achieves 10 Hz natural frequency. According to Farrat. (N.d.) damping coefficient is 0.01 – 0.05 with rubber/neoprene-based vibration isolators. Based on this information, transmissibility values for different excitation frequencies are presented in Table 13.

Table 13. Calculated transmissibility of system in different excitation frequencies

Excitation frequency [Hz]	**Frequency ratio (ω/ω_n)**	**Transmissibility**
24	2.4	0.20
35	3.5	0.08
50	5	0.04

Transmissibility for the lowest frequency energetic vibrations (24 Hz) is 0.20, therefore 80% of vibration energy is not transmitted to receiver. Transmissibility values for other high energy frequencies in spectrum are even lower, achieving almost complete isolation. Deflection with this isolator is around 3 mm. It must be considered when determining installation dimensions. If it is neglected, the scanner would be installed 3 mm too low.

3.8 Thermal analysis

The required heating power is calculated using outside temperature of -50 °C and cooling power with sol-air temperature of 59 °C. In both cases, the temperature inside scanner is 20 °C. To create a worst-case scenario, in cooling calculation all devices are switched on and in heating calculation they are off. The values of thermal flux through different surfaces and combined required heating and cooling powers are presented in Table 14 and Table 15.

Table 14. Cooling load components and total load

Load type	**Thermal load [W]**
Thermal gain through walls, doors, and vent tube walls	323
Thermal gain through windows	101
Internal device thermal power	252
TOTAL	676

Table 15. Required heating power values

Load type	**Heat loss [W]**
Heat loss through walls, doors and vent tube walls	559
Heat loss through windows	175
TOTAL	734

In final solution, a wall mounted cooler with total cooling power of 900 W is chosen – there is 30% extra capacity for safety. Heating is done with two 450 W electric flow-through heaters.

3.9 Embodiment design results

Below is described development of the rough layout and refining it into the final one. Results are presented in same order as the product is manufactured and assembled.

3.9.1 Rough layout

Most important size and arrangement defining components are the measurement instruments and any auxiliary components with significant dimensions. 3D-models of all components were modeled or downloaded from manufacturer website to create rough layout variants. Main function carriers – the laser scanners, cameras and lights were arranged first. Fans were modeled to visualize the viewing angles. A window opening through which the cameras look through was also modeled. The arrangement was done based on findings of previously done experiments.

Two types of chip conveyors in different widths were modeled to find the correct positioning for cameras. Other spatial constraints – the ceiling and walls were modeled according to measurements taken on installation site.

As visible in Figure 15, the scanning components are split into two halves (mirrored) which makes it possible to meet the low mass requirement. It also provides scalability for future designs – a middle scanner module could be added to extend the scanning width.

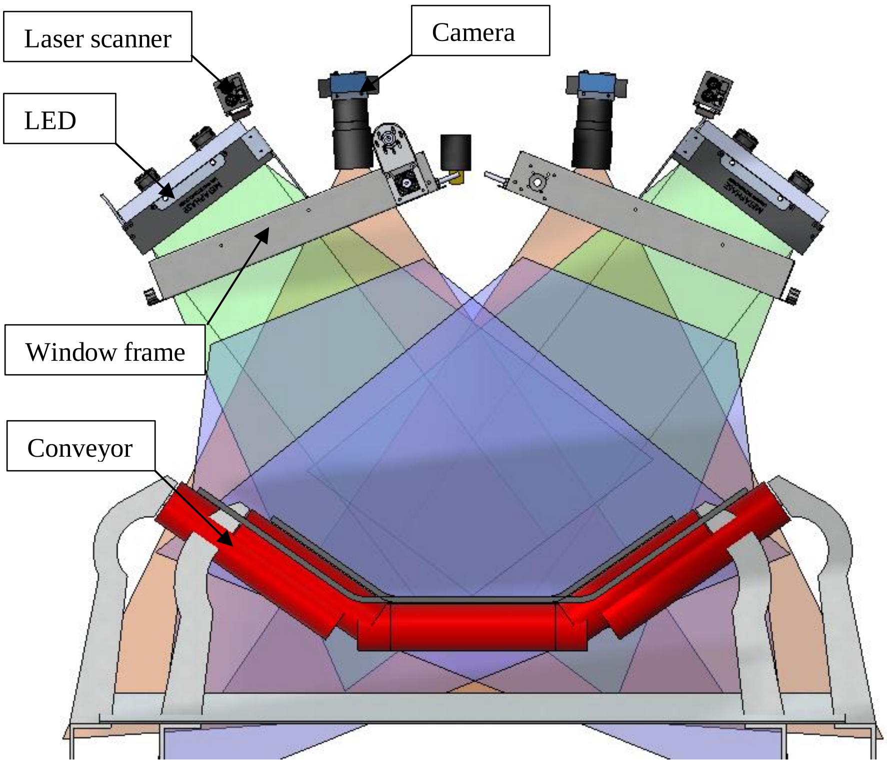


Figure 15. Rough layout of main function carriers: windows, lights, cameras, and lasers

Green color represents light beam, red the camera field of view and blue the laser scanning area. Size-determining auxiliary components – cooling unit, heaters, electric enclosure, and washer fluid tank were added to the assembly model (Figure 16). Arranging the scanner components proved out to be more straight forward than supporting components, which required more iterations.

Biggest challenge was finding a way to create airflow between modules and route the air fluently through the cooler and heaters. Three types of coolers were sketched as 3D model and arranged. At this point, the cooler power rating was based on estimate of wall area and thickness

Originally, the embodiment of auxiliary components was planned to consist of single module but upon closer inspection the mass turned out to be too high. Therefore, the components were split into two groups – support module and control module.

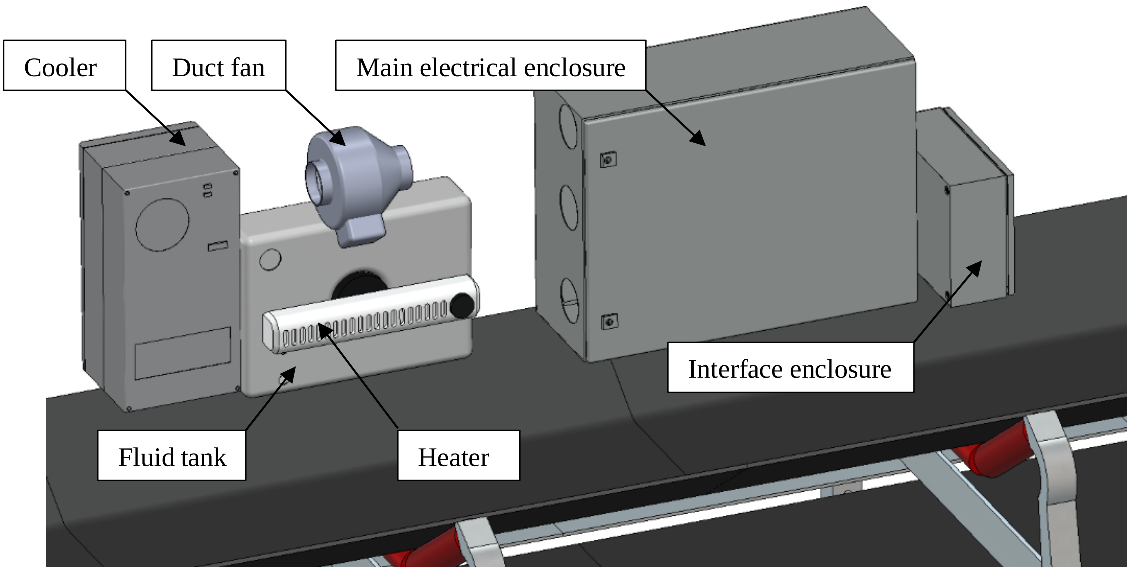


Figure 16. Rough layout of most important auxiliary components: cooler, fluid tank, heater, blower, and electrical enclosures.

Having set up all components roughly, everything else was built around it. The shell was sketched to contain all components with some space to spare. Doors were added and frames for components modeled. Locations of air vents and passageways of cables were roughly laid down before moving onto the next phase. Detailed design of all modules is described in next chapters.

3.9.2 Scanner module

Based rough layout, the steel outer frame was modeled from 30 x 30 mm RHS. Many iterations were required, as locations of components and arrangements were modified. The final frame construction is presented in Figure 17.

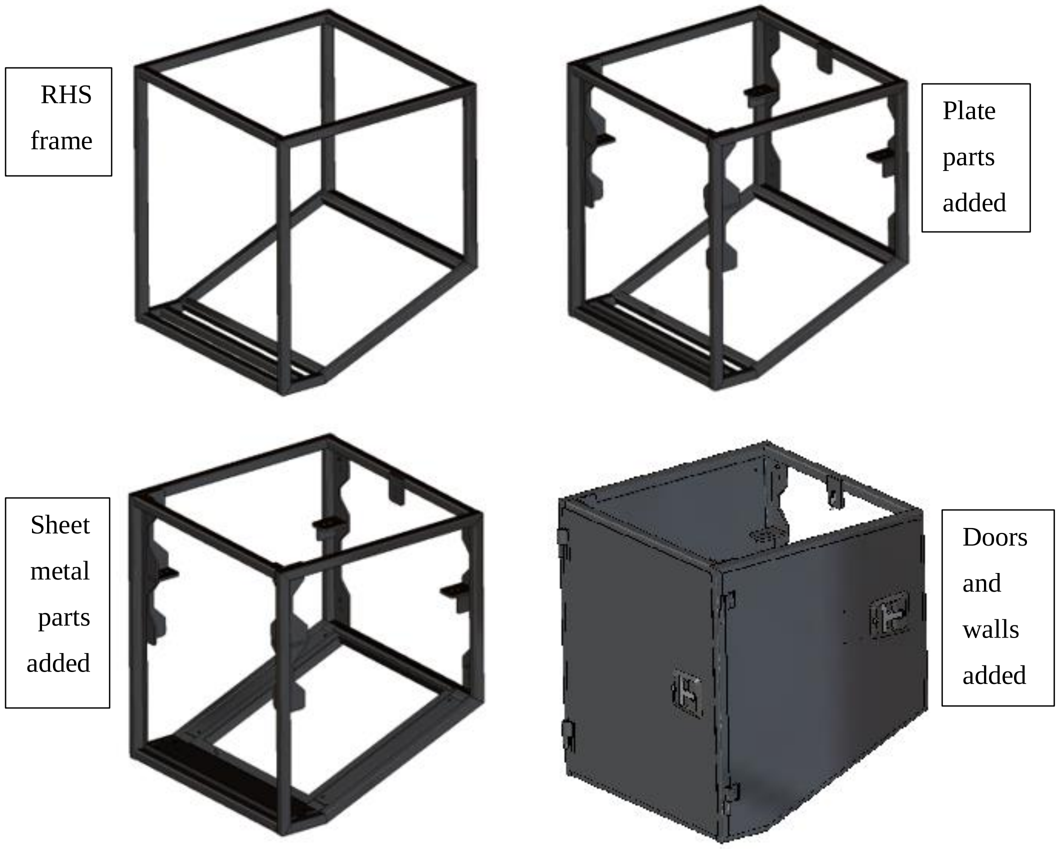


Figure 17. Scanner module outer frame step-by-step construction

Frame was designed with high interest in efficient manufacturing and assembly operation. The picture shows each step of frame construction. After cutting the tubes, a simple frame will be welded with jig (top left). Phase in top right shows self-locating plate parts added and next, the sheet metal parts are installed. Final step is installing walls and doors.

Door features RHS frame, glass fiber shells and double sealing. It is installed with weldable hinges. The door latch features a heavy-duty handle which works by turning and pushing the handle flush. The final pushing motion forces the door completely shut and slightly compresses seals, guaranteeing tightness. The latch itself also comes with IP65 certification.

The scanner module consists of two halves and therefore there are two mirrored configurations of the frame. Frame’s narrow side features diamond-shaped locating pins which are used to mate the scanner halves at exactly the right location.

Frame allows large openings for maintenance and easy installation of following subassemblies in the assembly process. The subframe, depicted in Figure 18, can be simply laid down through the top opening.

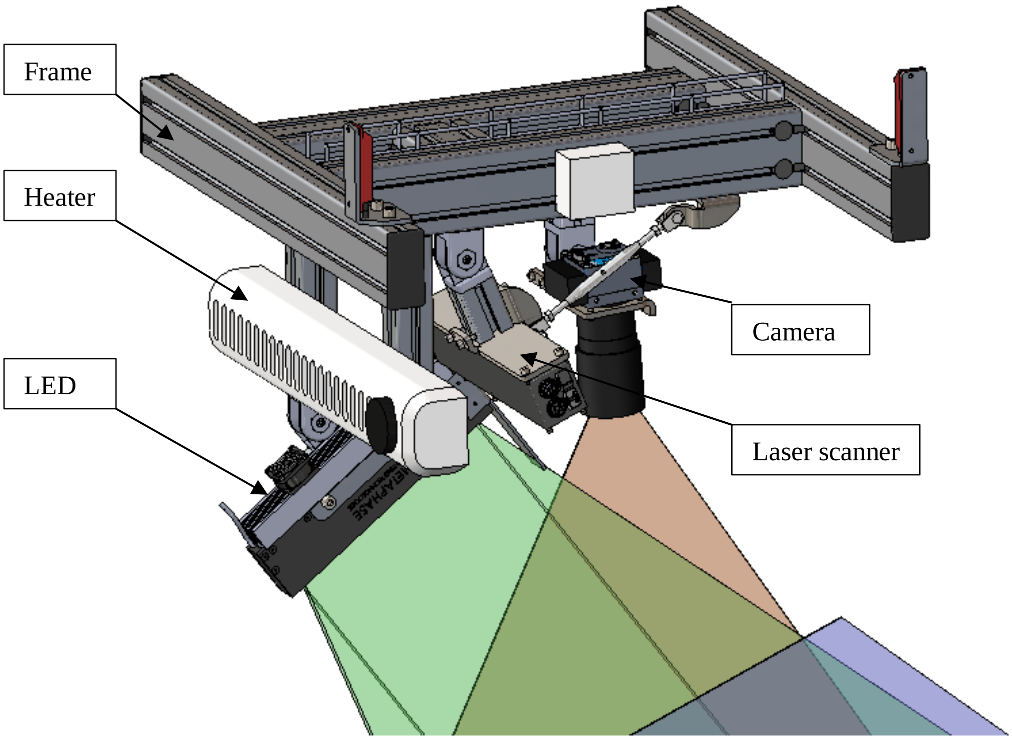


Figure 18. Aluminum frame of the scanner module with main components installed

The subframe is designed to be lightweight and easy to assemble and install. Superlight 40 x 40 mm and 40 x 80 mm aluminum profile classes are used. Precut and machined profiles are joined with universal fasteners.

Camera adjustments are done with locking hinges and adjusting mounts. The laser scanner and color camera have adjustment in 3 rotation axes and 2 translation. LED does not require precision aiming; thus, it was left only with tilting adjustment. Components are pre-installed to the frame and frame can be lowered down to the steel frame and fastened.

The scanner module halves are joined temporarily together, and cameras calibrated. Calibration is required because multiple cameras are used. After calibration, modules can be separated, and roofs installed. Figure 19 shows the finished module, ready to be transported to customer.

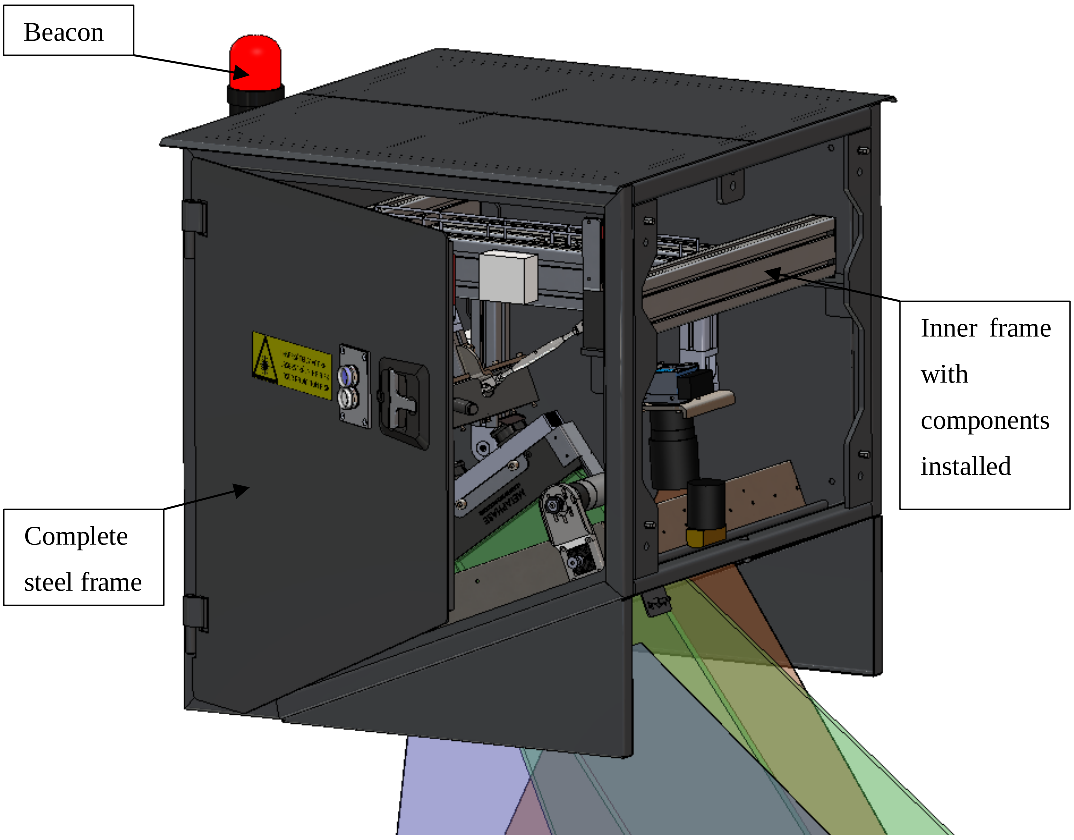


Figure 19. Finished scanner half with all components installed.

Doors are equipped with magnetic safety switches to shut down lasers if a door is opened. Information from safety switch is also used to turn off cooler when doors are open to prevent condensation. A safety-compliant label is mounted next to door handle. Window wipers are scaled down in size from existing design and modified to use dual end switches and DC motor.

3.9.3 Support module

This module (Figure 20) is responsible of cooling, heating, and supplying washing fluid to the window washers. Frame design is similar to the scanner module – manufacturing is the same, only main dimensions are different. Also, assembly method of fabricating steel frame and dropping in a finished subassembly remains here.

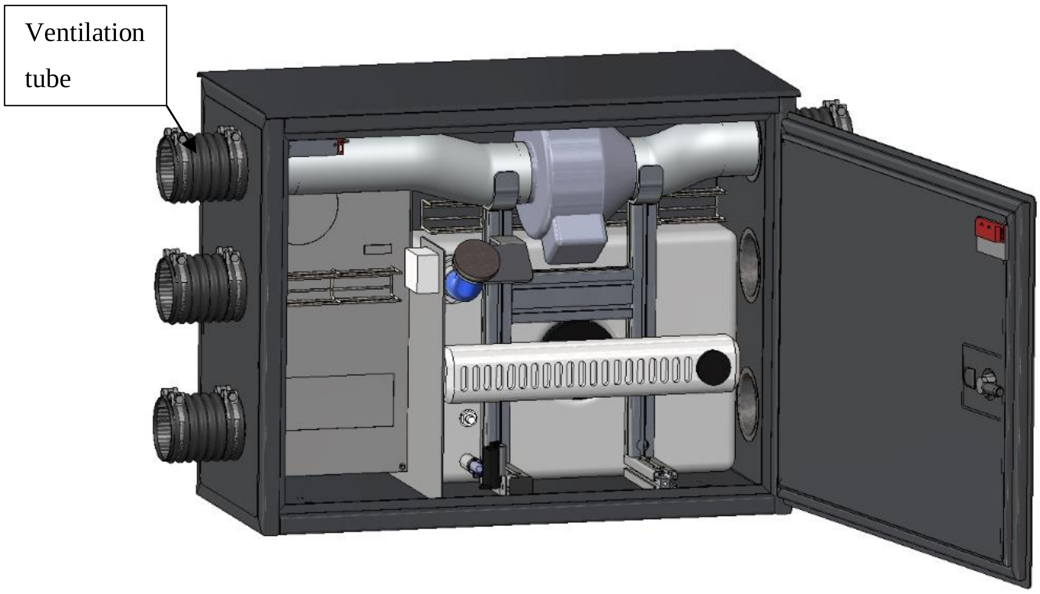


Figure 20. Support module with all components installed

A duct blower moves air between all modules in a closed circulation. When flow moves through the support module, it passes through heater and cooler. Both are PLC-controlled to regulate temperature.

Fluid tank is fitted with pump, solenoid valve, fluid level sensor and refill tube. It supplies washing fluid for glass washer system. Interface between modules is done with steel reinforced polyurethane tubing – two passages are for air circulation and one for cabling.

3.9.4 Control module

The purpose of the module is to house the main electrical enclosure and interface enclosure. Finished assembly is depicted in Figure 21.

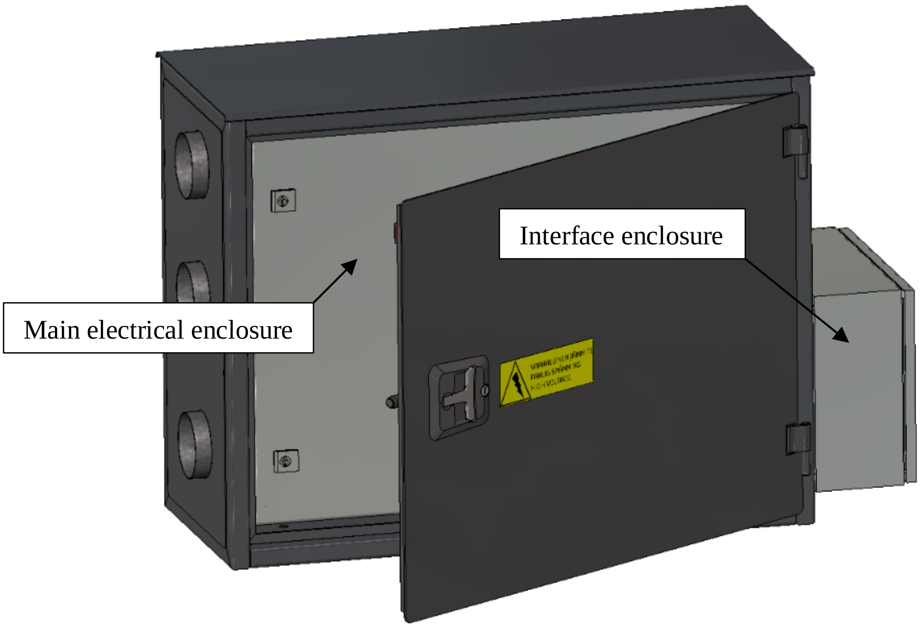


Figure 21. Control module

All connections to the outside are done through the interface signal box. This study will not cover the automation design but that will be left to expert of that field. The framing is identical to the support module, only internal parts differ. Shell protects from weather and provides thermal isolation.

3.9.5 Stand and covers

The stand of scanner is presented in Figure 22. The frame construction is based on I-beams and RHS. Besides holding the scanner, the stand features covers, which prevent direct vision into the laser source.

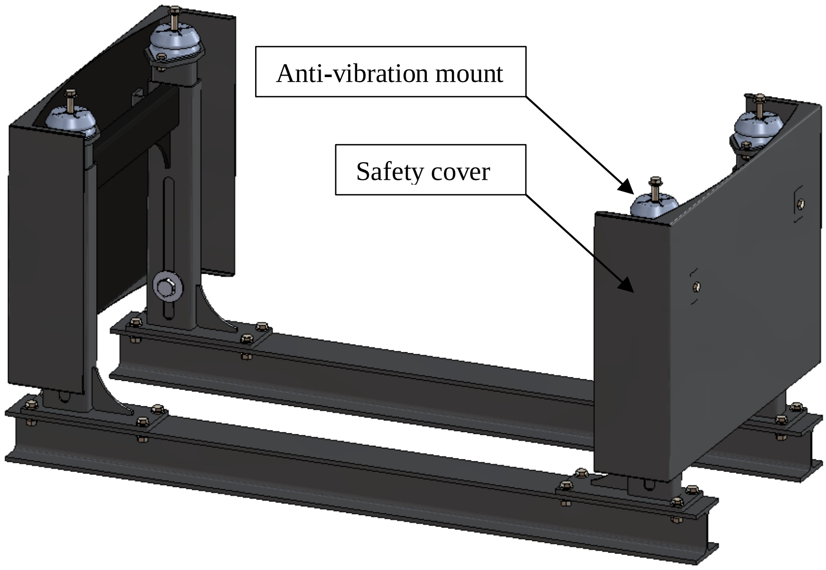


Figure 22. Stand of scanner module with anti-vibration mounts and safety covers

The scanner is mounted to stand using M12 screw joints. The anti-vibration mouths are installed between the stand and scanner.

Design-recycling is utilized. Nearly identical stand assembly is used for all modules, as well as maintenance platform. The columns of stand are totally recycled subassemblies, which is beneficial for DFMA. They can be manufactured and transported in logical entity and combined to form the final assembly easily.

3.10Final design

The complete system is presented in Figure 23. From left to right, the system consists of maintenance platform, scanner module, support module and control module. Average sized human is added to visualize scale.

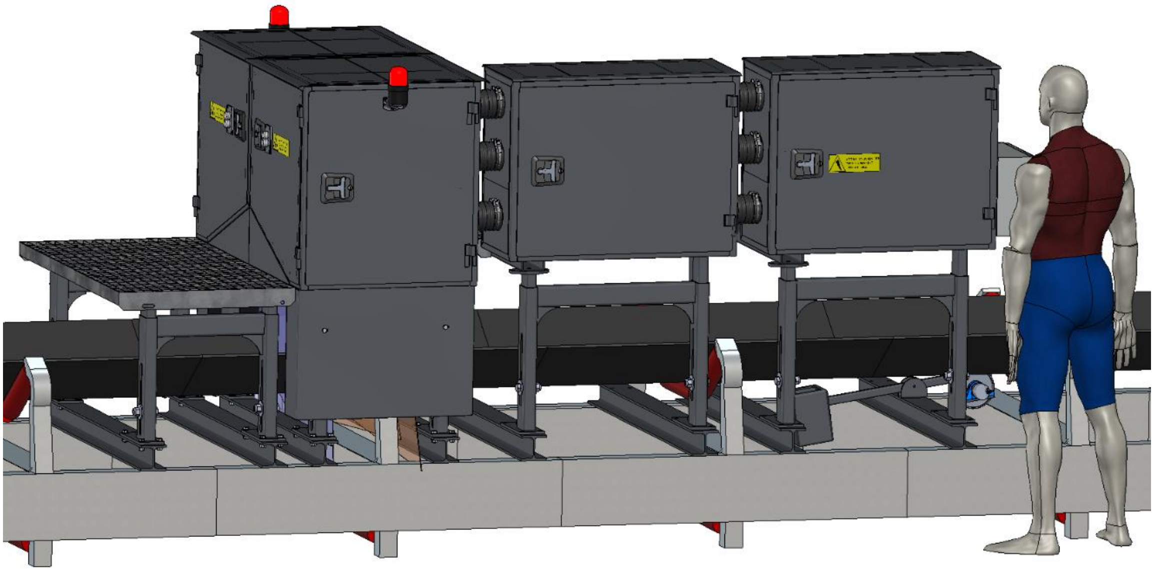


Figure 23. Final system

4 ANALYSIS

Complete design of chip scanner was achieved as a result of this study. The final system is transported to installation site in compact ang lightweight modules and quickly installed and wired. Well-chosen instruments and optimally arranged camera setup guarantee accurate measurement data, to which vibrations and temperature variations have minimal effect on. Maintenance can be done with ease thanks to maintenance platforms and conveniently placed doors.

The design fulfills all the demands in requirement list. Some of the wishes had to be abandoned to avoid too much complexity. The goal was to have a complete 3D model ready for making of drawings, which succeeded. This is the first iteration of design, so there are certainly some aspects to improve. This study consists of so many different details, not all of them could be focused on so closely as the author would have wanted to. Design review by other engineers would also be beneficial. Some remarks about the results are presented below.

4.1 Vibration

Vibration isolation achieved with the selected mount is 80%. Prototyping and measurements are required to assess whether more isolation is needed. If larger isolation is required, the scanner mass could be increased, and larger anti-vibration mounts selected. This would lower the natural frequency of vibration receiver.

4.2 Modularity

The main reasons why modularity was needed were transport and installation. Solution was found to fulfill both. The scanner consists of two halves, which are separated for transportation and joined at installation site. Also, other modules are compact.

One benefit that modularity brings is that the arrangement of measurement system can be tailored to fit a specific site. In this initial design, all modules are arranged after each other, which takes lot of space along the conveyor. Because of narrow passageway and low ceiling, this was the only possible setup. In future, if there is limited space along conveyor but more space elsewhere, the modules could be arranged differently to adapt to the space.

4.3 DFMA

Design for manufacture and assembly is visible in results mostly as simple components and standardized design of subassemblies. Subassembly recycling was used in steel frame and doors and stand. Self-locating plate parts were used where applicable. Sheet metal parts dimension tolerance is done so that they fit regardless of possible misalignments caused by welding. Standardized and as far processed materials as possible were used.

As conclusion, DFMA has been taken into account during work but there are certainly improvements to be made, as this design is the first version. Building first prototype and documenting assembly times and any issues faced could enhance DFMA performance greatly.

5 DISCUSSION

In this chapter, the key findings are presented along with short sensitivity and objectivity assessment. Utilization of results and future research topics are discussed. In the final chapter, the thesis is summarized.

5.1 Key findings

Answers were found for all research questions. The first question was what is the best solution for complete scanner design, including instrument frames, mountings, protective shell, installation mechanism and electrical routings? Solution for design was found. The "best solution" is of course subjective matter. But in this case, multitude of systematic methods were used and the result they yield should be as close to optimal solution as possible.

The second question was what factors affect the interference to laser scanning caused by light and how to prevent them. It was noticed that the type of light and arrangement of laser and light with reference to glass are most affecting. Optimal arrangement was found that cancels all interference.

The third question, how to prevent any harm to measurement caused by vibrations, temperature variation and dirt, was also answered. Anti-vibration mounts were selected based on measured vibration spectrum. Thermal insulation and cooling and heating solutions are used to regulate temperature. IP54 enclosure, external components and window wipers make sure the cameras do not have problem with dirt.

Final research question was how to choose measurement instruments for this application. Correct instruments were selected based on literature review on measurement technology, manufacturer datasheets and evaluation criteria.

5.2 Sensitivity and objectivity

Sensitivity analysis is not applicable to the main content of this work, as it is practical work and difficult to present with numbers or measurements. However, to the experiments done with cameras and lasers it could be applied. For those, it is clear that not enough observations were taken, and they were taken at too large spacing from each other.
Such approach was considered safe because creating any general models for interference was not the goal, results that apply only to this scanner model would be satisfactory.

The author has previous experience of scanner design, so all the decisions are probably not totally objective. Even in the systematic design process, this could have had an effect. Objectivity could be further increased by doing this type of projects in a team – more experts lead to more balanced decisions.

Furthermore, giving this type of design project to a person who has never seen any industrial machine vision system might lead to some fresh ideas that never would come up inside experienced team.

5.3 Utilization of results

Results are classified as scientific, concrete applications and generalized results.
Due to highly specialized application, the results have little scientific value. The only thing that have some scientific use are the experimental results. Even those are very limited.

The most valuable result is the concrete application. When generalized, the results could see daylight in countless other applications. The scanner architecture could be scaled in size and modified for other applications. Also, different functional modules can be added.

5.4 Future research

This thesis focuses on the mechanics of system. Further development is needed in automation/electric and software design.

Many aspects of this work must be tested and verified by prototyping. When building, any problems must be well documented and used to improve DFMA. The test required by IP class need to be conducted. Things such as vibration isolation, heating, cooling, and air circulation can be easily verified when the unit is placed to the installation site.

The design itself could be further improved by modeling different module arrangements – for example, the control module could be placed next to scanner to make the unit more compact. For special conveyors that are wide, the scanner module could be extended by adding an extension unit in between the current scanner halves.

5.5 Summary

The initial practical problem was the lack of valid design for chip scanner to measure quality and volume flow of chips. The measured data is valuable both for producer and purchaser of chips. Producer gets instant feedback data to control the chipping process and basis for price-determination. For the purchaser of chips (e.g. pulp mill) the information about chip dimensions and quality can bring huge value to controlling the pulping process.

The goal was to invent an overall solution fulfill the objective. Issues to measurement caused by dirt, light, vibrations, and temperature variations had to be solved. Systematic design approach was used and complemented with vibration analysis, thermal analysis, DFMA, material selection and experimental design. All the methods were used together and after many iterations of modeling, the work was completed.

The result is satisfactory, as it fulfills all requirements in the requirement list and answers to research questions were found. However, the true performance of system will only be revealed after it is manufactured and tested as prototype.

LIST OF REFERENCES

Allen E., Triantaphillidou, S. 2012. The Manual of Photography, Tenth Edition. Focal Press. 566 p.

Al-Saud, K. 2009. Measured versus Calculated Roof Peak Sol-air Temperature in Hot-arid Regions. Journal of Architectural and Planning Research Vol. 21. Pp. 1-7

AMC Mecanocaucho. N.d. Anti-vibration mounts. [web-document] AMC Mecanocaucho. [Accessed 4.11.2019] Available as PDF-file: http://www.mecanocaucho.com/download/catalog/cauchometal_en.pdf

AZoSensors. 2014. An Introduction to Laser Triangulation Sensors. [web-document]. AZoSensors. [accessed 28.12.2019] Available at: https://www.azosensors.com/article.aspx?ArticleID=523

Bishop, R. 2002. The Mechatronics Handbook. CRC Press. 1229 p.

Childs, P. 2019. Mechanical Design Engineering Handbook. Elsevier. 982 p.

Dean, A., Voss, D., Draguljić, D. 2017. Design and Analysis of Experiments, Second Edition. Springer. 852 p.

Eskelinen, H., Karsikas, S. 2013. VIHREÄN TEKNOLOGIAN NÄKÖKULMAT KONSTRUKTIOMATERIAALIEN VALINNASSA. Lappeenrannan teknillinen yliopisto. 364 p.

Farrat. N.d. Detailed Vibration Isolation Theory. [web-document]. Farrat. [Accessed 21.3.2020] Available at https://www.farrat.com/resources/detailed-vibration-isolation-theory

IEC 60825-1. 2001. Safety of laser products – Part 1: Equipment classification, requirements and user’s guide. Switzerland: International Electrotechnical Commission. 122 p.

Keyence. N.d. Sensor head – LJ-X8900. [web-document]. Keyence. Available at: https://www.keyence.com/products/measure/laser-2d/lj-x8000/models/lj-x8900/

LMI Technologies. N.d.-a. Ultra High-Resolution 3D Laser Line Profile Sensors. [web-document]. LMI Technologies. Available at: https://lmi3d.com/products/gocator/g2/2400-series/laser-line-profile-sensors

LMI Technologies. N.d.-b. Dual Triangulation 3D Laser Line Profile Sensors. [web-document]. LMI Technologies. Available at: https://lmi3d.com/products/gocator/g2/2800-series/laser-line-profile-sensors

Machine Design. 2002. Optical Shaft Encoders. [web-document]. Endeavor Business Media. [accessed 9.12.2019] Available at: https://www.machinedesign.com/automation-iiot/article/21812928/optical-shaft-encoders

MoreSteam. N.d. Design of Experiments. [web-document]. MoreSteam. [Accessed 19.2.2020] Available at: https://www.moresteam.com/toolbox/design-of-experiments.cfm

Norton, M., Karczub, D. 2003. Fundamentals of Noise and Vibration Analysis for Engineers. Cambridge University Press. 651 p.

Pahl, G., Beitz, W., Feldhusen, J., Grote, K.H. 2007. Engineering design - A systematic approach. 3rd edition. Springer. 617 p.

ReVelle, J. 2002. The Manufacturing Handbook of Best Practices. CRC Press. 425 p.

SFS-EN 60529. 2019. Degrees of protection provided by enclosures (IP-code). SFS. 108 p.

Sixta, H. 2006. Handbook of Pulp. Wiley-VCH Verlag GmbH & Co. KGaA. 1352 p.

Spitler, J. 2009. Load calculation applications – SI Edition. Atlanta: ASHRAE. 346 p.

Teledyne DALSA. N.d.-a CCD vs. CMOS. [web-document]. Teledyne DALSA. [accessed 3.1.2020] Available at: https://www.teledynedalsa.com/en/learn/knowledge-center/ccd-vs-cmos/

Teledyne DALSA. N.d.-b Line Scan Primer. [web-document]. Teledyne DALSA. [accessed 3.1.2020] Available at: https://www.teledynedalsa.com/en/learn/knowledge-center/line-scan-primer/

The Concrete Centre. N.d. Thermal Mass Explained. [web-document] The Concrete Centre. [Accessed 2.2.2020] Available as PDF-file: https://kivifaktaa.fi/wp-content/uploads/2017/02/Thermal-Mass-Explained.pdf

Experiment log – Laser interference test

Date: 18.2.2020

The used light type and its location are listed for all IDs. Distances are planned locations and not measured locations. In control cases 000 and 020, the light is switched off. Resulting data from test is depicted in Appendix II.

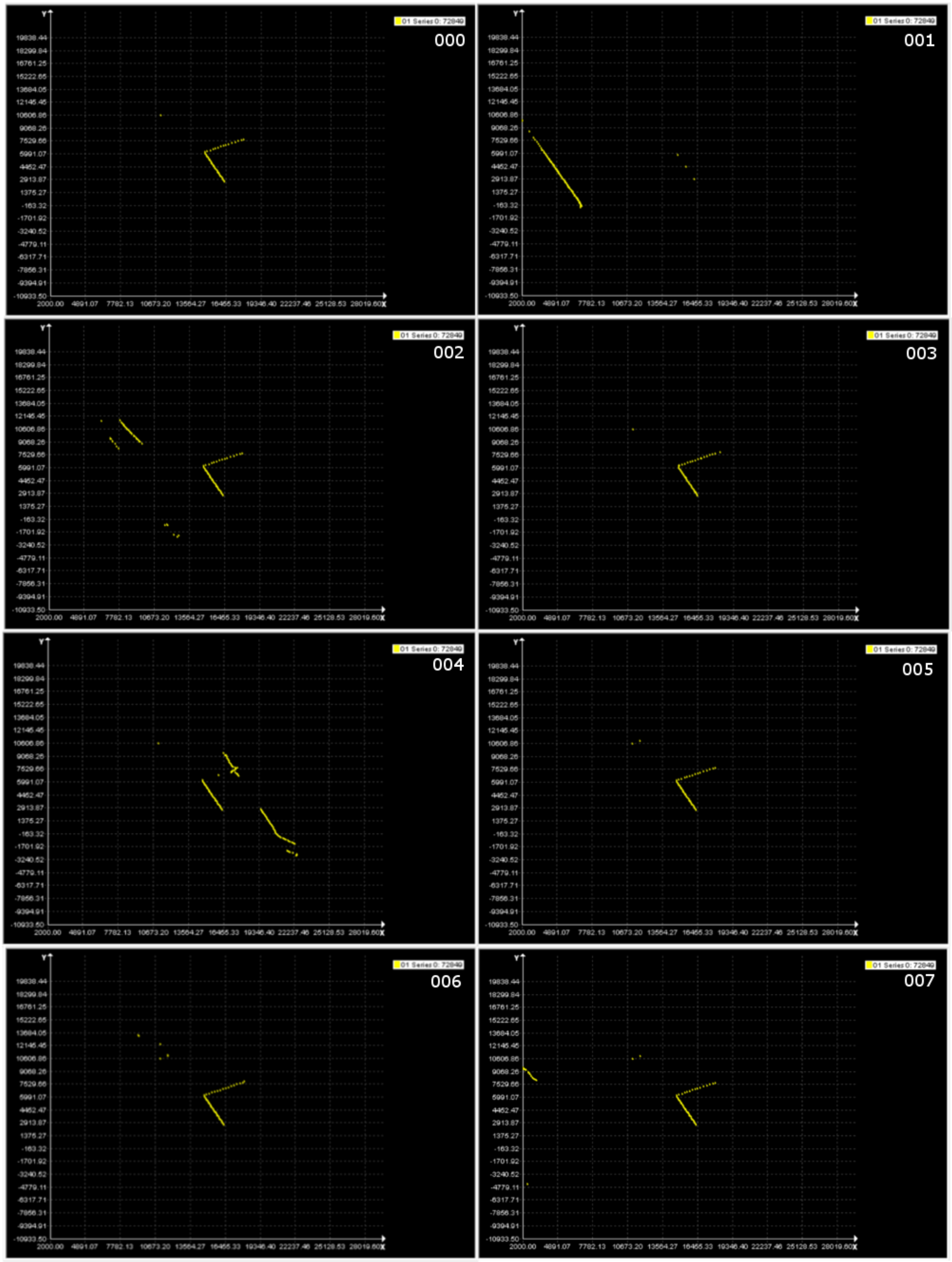
ID	**Light type**	**Distance to glass (A)**	**Lateral distance (B)**
000	Switched off		
001	Collimated LED	200	50
002	Collimated LED	200	100
003	Collimated LED	200	150
004	Collimated LED	200	200
005	Collimated LED	200	250
006	Collimated LED	200	300
007	Collimated LED	200	350
008	Collimated LED	200	400
009	Ordinary LED	200	50
010	Ordinary LED	200	100
011	Ordinary LED	200	150
012	Ordinary LED	200	200
013	Ordinary LED	200	250
014	Ordinary LED	200	300
015	Ordinary LED	200	350
016	Ordinary LED	200	400
020	Switched off		
021	Collimated LED	100	50
022	Collimated LED	100	100
023	Collimated LED	100	150

Experiment log – Laser interference test

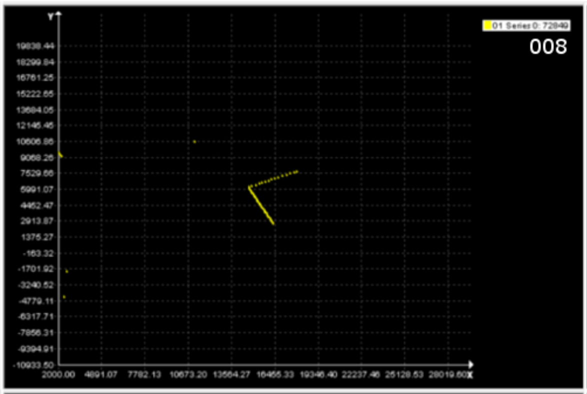
024	Collimated LED	100	200
025	Collimated LED	100	250
026	Collimated LED	100	300
027	Collimated LED	100	350
028	Collimated LED	100	400
029	Ordinary LED	100	50
030	Ordinary LED	100	100
031	Ordinary LED	100	150
032	Ordinary LED	100	200
033	Ordinary LED	100	250
034	Ordinary LED	100	300
035	Ordinary LED	100	350
036	Ordinary LED	100	400

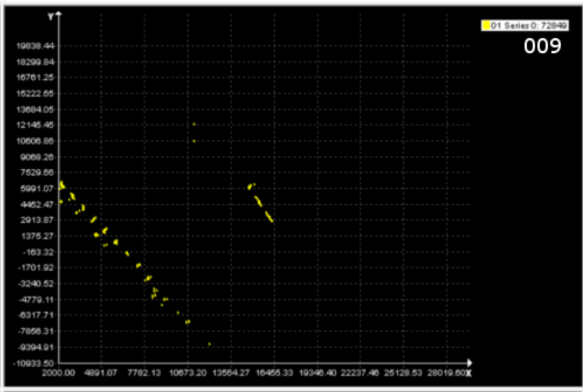
Experiment data – Laser interference test

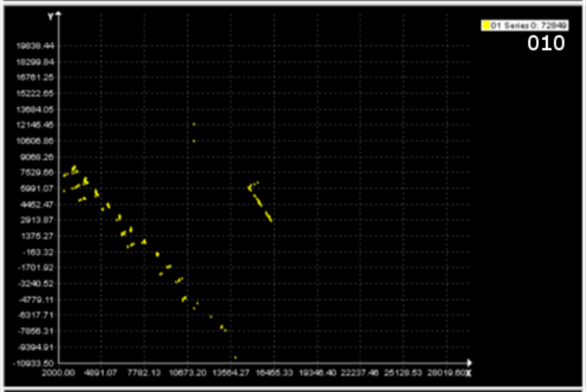
For each case, the related parameters can be found in Appendix I.

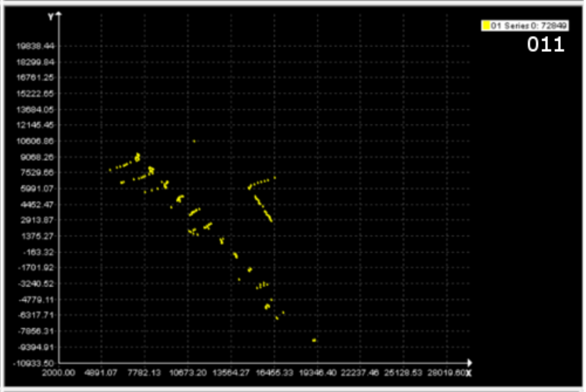


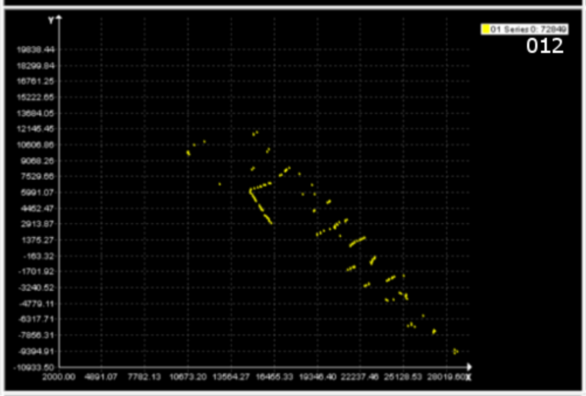
Experiment data – Laser interference test

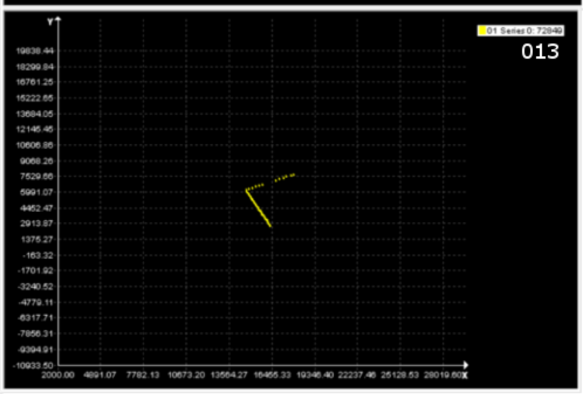


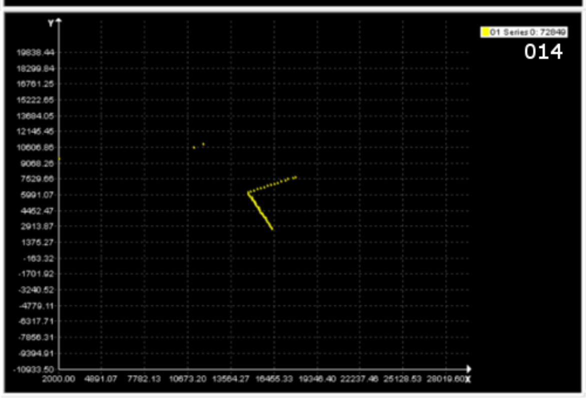


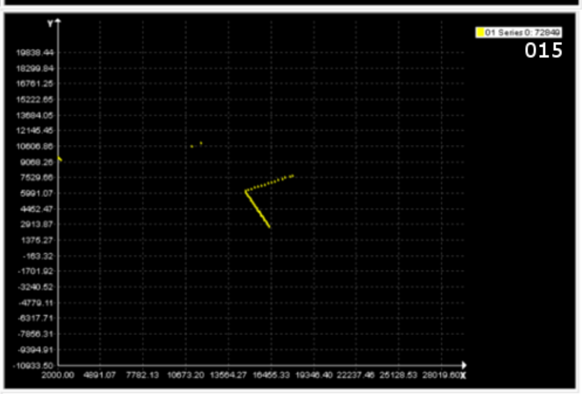




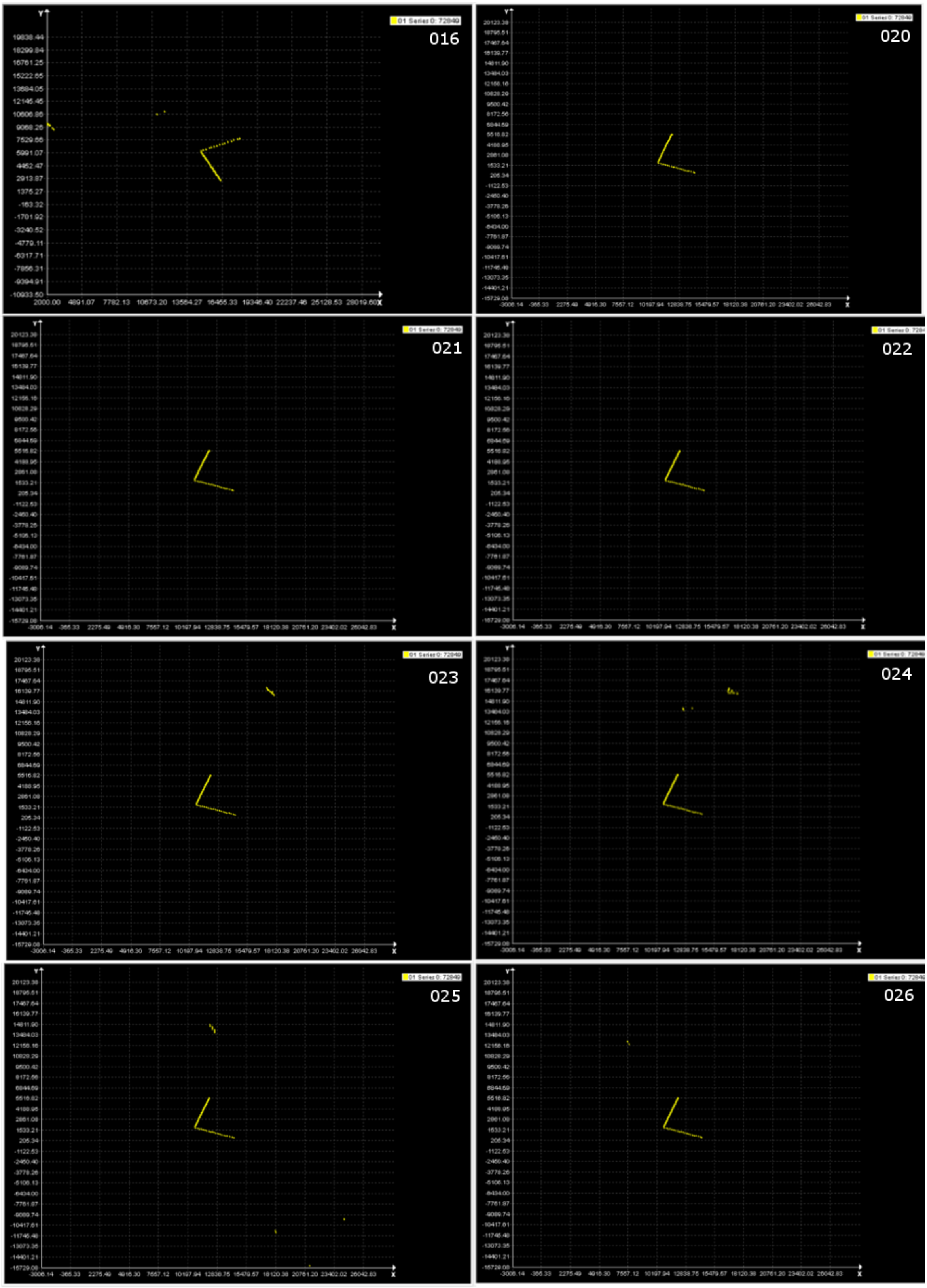




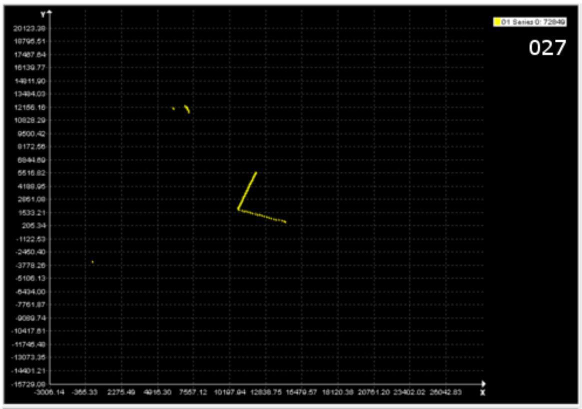


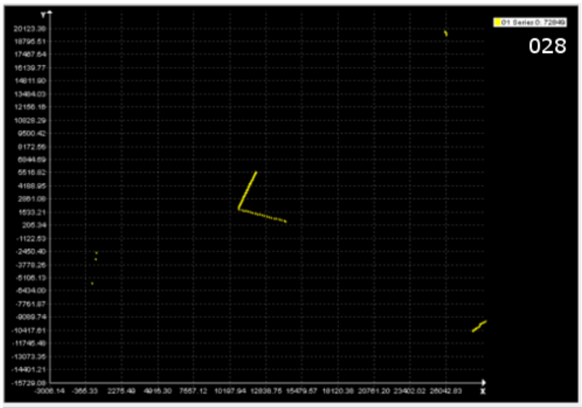


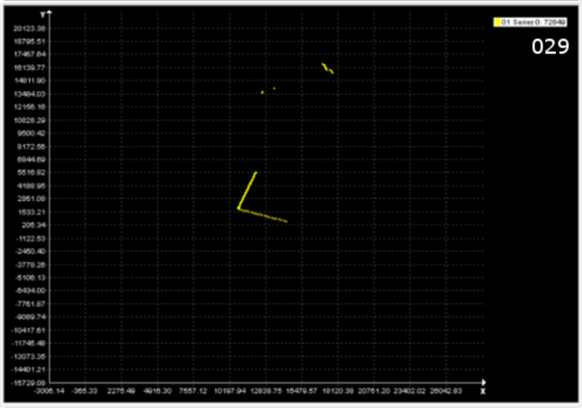
Experiment data – Laser interference test

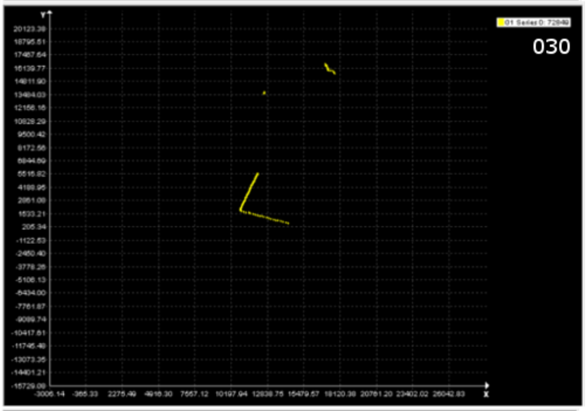


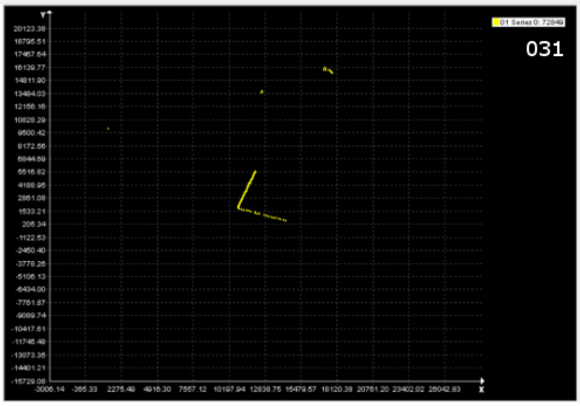
Experiment data – Laser interference test

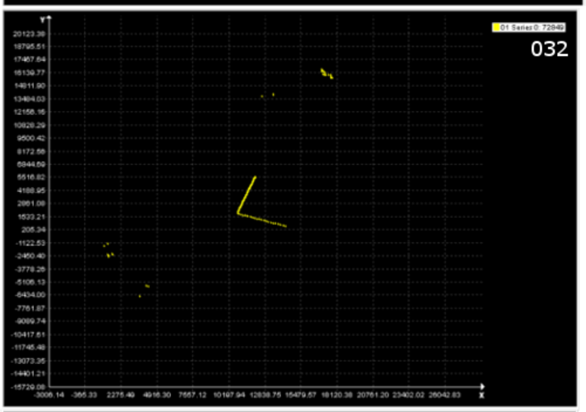


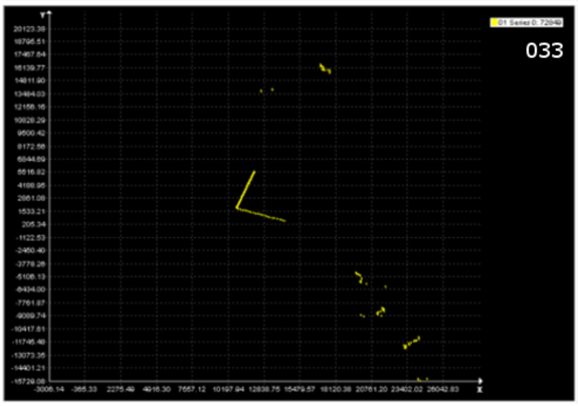


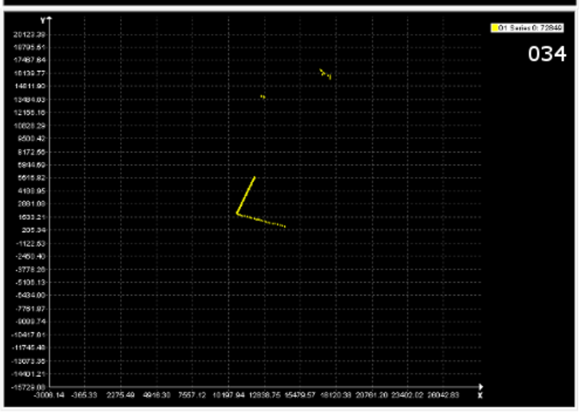




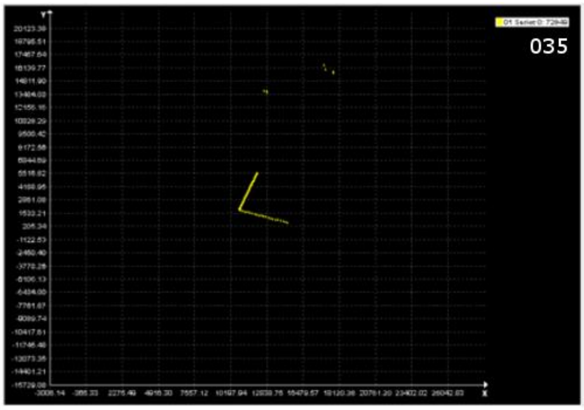


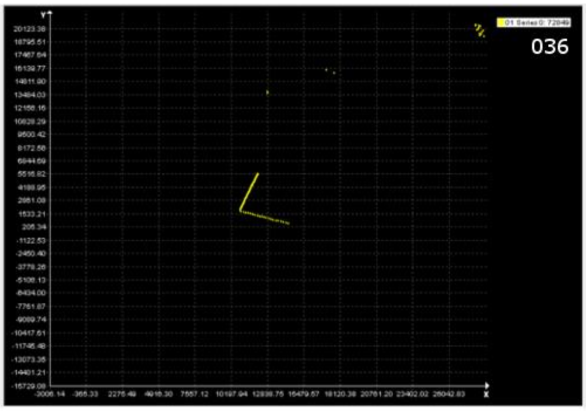






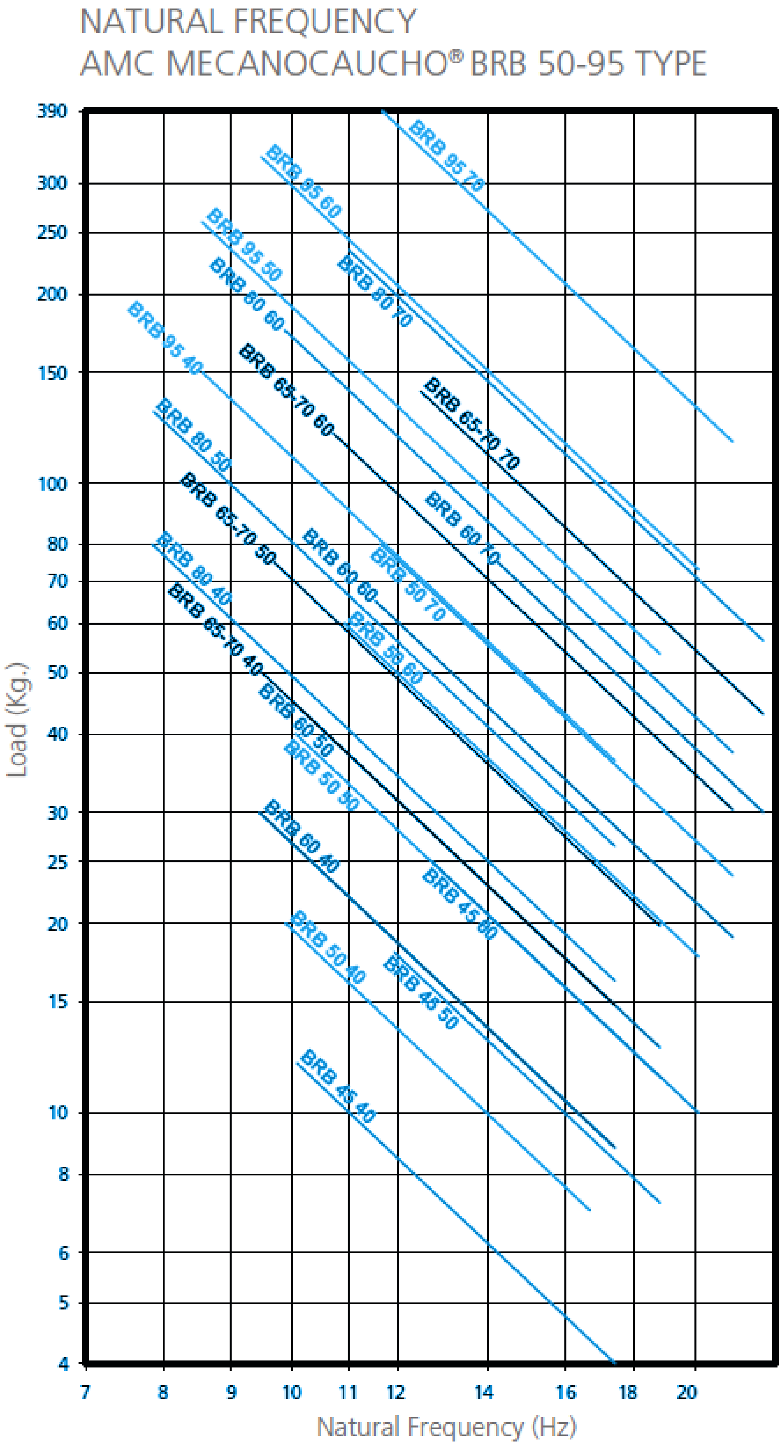
Experiment data – Laser interference test





APPENDIX III

Natural frequency versus mass graph for anti-vibration mount selection (AMC Mecanocaucho n.d. p. 17)



APPENDIX IV

Load deflection graph for anti-vibration mount selection (AMC Mecanocaucho n.d. p. 17)