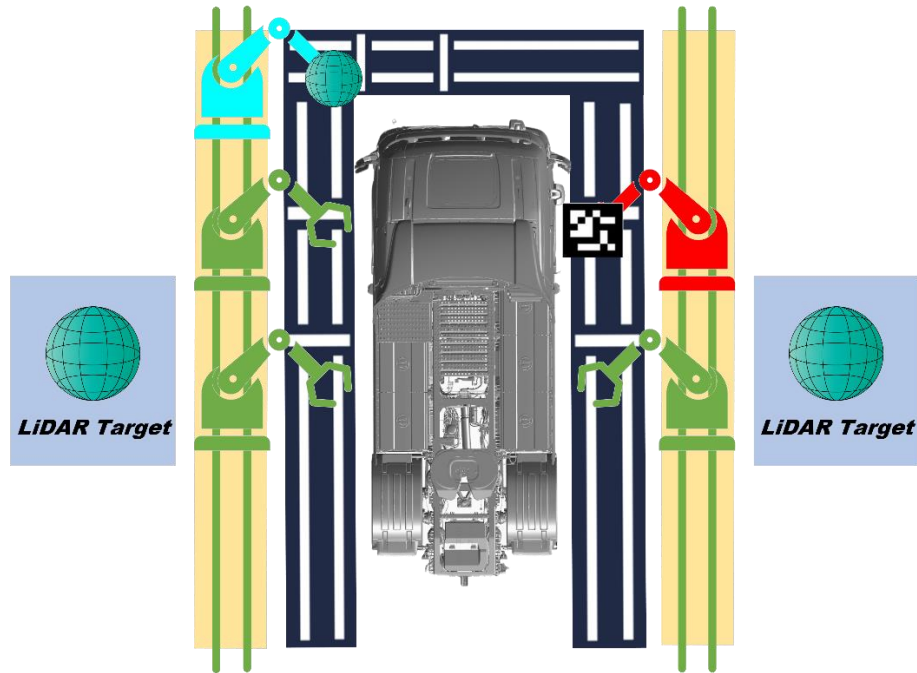




CHALMERS
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Calibration of Perception Sensors

Master's thesis in Product Development & Production Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023

MASTER'S THESIS 2023

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Cover: Calibration station concept for a high-volume factory

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Abstract

New regulations mandating specific sensors coupled with the trend towards manufacturing trucks with more self-driving capabilities has led to an increase in both the number and types of perception sensors on each new model of trucks. With each new model, the need for proper calibration becomes paramount and demands an investigation into what sensor technologies will be required to reach a higher level of autonomy. Further, proper calibration is paramount to ensure the accuracy concerning the physical location of the objects in the truck's surrounding and allowing the truck to safely navigate.

This thesis therefore explores perception sensors in the context of manufacturing trucks. The research investigates the currently employed calibration methods used for trucks and various calibration methods for different sensors. Both quantitative and qualitative data was gathered from an in depth AS-IS analysis and a literature study on both calibration methods and the sensor technologies themselves. This is done in order to form the basis for recommending concepts of future calibration stations.

The results presented in this thesis include three variations of a high-volume factory calibration station and one variation for a low-volume factory. The four different concepts all utilize the same calibration methods; however, the pieces of equipment and layouts differ among them. The concepts are capable of handling camera, LiDAR, camera stitching and Radar, with different process times.

The conclusion is therefore that both low and high-volume factories should share the same calibration methods enabling interoperability and scalability. The difference between them is the amount of equipment and investment needed. For high-volume factories where time is critical and multiple cobots are employed and utilizes parallel calibration. In contrast, low-volume factories where time is not as critical fewer cobots are employed and utilizes sequential calibration. This in turn entails that high-volume concepts need greater investment and are more complex. Nonetheless both concepts can benefit from shared knowledge and resources.

The proposed concepts serve as a foundation for future calibration stations where trucks of a higher degree of autonomy can be produced.

Keywords: Calibration, Sensor, Perception sensors, Radar, LiDAR, Camera, Camera Stitching, Point Cloud

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List of Acronyms and Abbreviations

ADAS	Advanced Driver Assistance Systems
FMCW	Frequency Modulated Continuous Wave
IF	Intermediate frequency
DSP	Digital Signal Processing chips
CW	Continuous wave
MMICs	Monolithic microwave integrated circuit
LiDAR	Light detection and ranging
Radar	Radio Detecting And Ranging
ToF	Time of Flight
OPA	Optical Phase Arrays
MEMS	Microelectromechanical systems
APDs	Avalanche Photodiodes
FOV	Field Of View
MOS	Metal-Oxide Semiconductors
CCD	Charged-Coupled Device
CMOS	Complementary Metal Oxide Semiconductors
QD	Quantum Dots
FLC	Front Looking Camera
FLR	Front Looking Radar
Cobots	Collaborative robots

1 Introduction

The general trend towards manufacturing trucks with self-driving capabilities in combination with new laws mandating specific sensors on new models of trucks, lead to more and more sensors being installed on each new truck model [1]. Additionally, to achieve these higher levels of self-driving capabilities more sensor types will be required [2]. This calls for greater emphasis on calibration but also on investigation of different sensor technologies that can contribute to reaching higher levels of self-driving capabilities.

Calibration of the perception sensors on the truck is crucial as it ensures that the physical location of objects, including pedestrians and other vehicles, is accurately reflected, which is critical for the truck to safely navigate its surroundings. The precise calibration of these sensors to the specific truck also contributes to the overall performance and functionality of the vehicle's Advanced Driver Assistance Systems (ADAS) and the vehicles' self-driving capabilities. Additionally, tolerances during the manufacturing process can result in small shifts in the sensor's location on the truck, making calibration essential to ensure accuracy of gathered data.

Further, time is a critical factor that imposes significant constraints on calibration procedures in a practical production line. Additionally, the current calibration station has reached its maximum capacity to accommodate additional sensors to be calibrated at the station. This leads to the necessity of investigating how a future calibration station can be designed and configured for a factory environment and what calibration methods should be employed. These methods should enable calibration of trucks with higher self-driving capabilities, while ensuring accuracy and adhering to any imposed time constraints.

1.1 Background

Vehicle autonomy can generally be structured into six different levels ranging from level 0 – no automation up until level 5 – full automation [1]. An illustration of the different levels of autonomy can be seen in Figure 1. As a vehicle increases on the autonomy scale, the required functions and capabilities it must perform continue to expand up until level five where the presence of driver is no longer required.

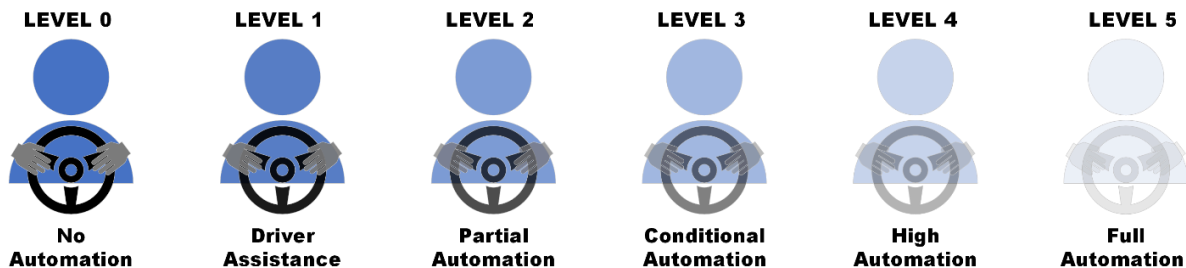


Figure 1 - Illustration of different levels of autonomy, adapted from [3]

Most trucks that are being produced by large truck manufacturers, such as Volvo Trucks, are at level one or two on the automation scale [4]. These levels are achieved when certain systems are

implemented into the vehicle that automate specific elements. These systems can include adaptive cruise control, lane-keeping assist, ADAS, automatic emergency breaking, blind-spot detection, and others. In the present-day trucks produced by Volvo, the gathered information for the systems comes from Radar and camera sensors. In the future, truck manufacturers, such as Volvo, want to produce trucks which are higher on the automation scale. This will require larger quantities of information to continuously be extracted from the truck's surroundings, but also require handling of different information types for the systems to function properly [5]. The information required would include data regarding road conditions, location of the vehicle, weather, obstacles, and movements of other vehicles. For the vehicle to be able to gather this varied information, different types of sensors will need to be present. Previously performed comparative studies within this field suggested that the types of sensors required for gathering of the necessary data are Radar, LiDAR and camera working in unison [2] [3]. For example, Radar sensors to detect other vehicles and their distance and speed, camera sensors to provide visual images of the environment surrounding the vehicle and LiDAR sensors to create a 3D map of the vehicle's surroundings.

This increase in both the number of sensors and sensor types will make it paramount for proper calibration. However, despite the growing importance of calibration there has been lack of prior research into how a calibration station should be designed to effectively handle this increase in variety and number of sensors. Therefore, Volvo wants to ensure their factories have the tools and equipment necessary for handling this predicted increase. The research presented in this thesis is therefore related to the equipment and methods used to calibrate these sensors.

1.2 Problem Definition

There is a pressing need for a calibration station that can perform calibration of camera, Radar and LiDAR sensors all in one location, to facilitate the production of trucks of a higher degree of automation. This need has occurred due to the capacity of the current station being at the point where it can no longer take in additional sensors for calibration. This will result in a serious problem as it will hinder the ability to calibrate new sensors within the appropriate time, leading to an overall inefficiency in the process at the factory. To address this issue, this thesis will be focused on the development of a calibration station that can effectively and efficiently calibrate the sensors utilized in production of upcoming trucks, as they will progressively advance along the autonomy scale, steadily achieving higher levels of autonomy.

Therefore, this thesis research questions are the following.

- How does the current station handle the calibration of perception sensors?
- What calibration methods exist for the different types of perception sensors?
- How can a future standalone calibration station be designed to meet the growing demands on calibration for trucks with a higher level of autonomy, while also bridging the gap between the existing calibration station and the anticipated requirements of a future one?

1.3 Delimitations

The delimitations taken within this research will be the following:

- The focus of this research will be on the calibration process and optimizing it. Hence, the design and development of the sensors will not be considered. Instead, some background information about the technologies will be presented.
- The area of application will only be for truck manufacturing sites.
- The research will only give suggestions on perception sensor calibration and will not include factors such as how to conclude the trucks position in the station. Instead, the thesis will give requirements on what kinds of information is needed for the calibration to be executed.
- There is no cost restriction to the suggested concepts for low-volume and high-volume factories, but it will be a subject of further investigation in future

2 Methodology

The methodology utilized in this thesis is the mixed methods approach which means that both quantitative and qualitative data was collected. A mixed method approach was necessary due to information and data being needed both concerning technologies and working procedures at the current station. The quantitative data was collected from both literature study, regarding methods used to calibrate perception sensors, and observational data regarding the equipment and systems present at the current station. While the qualitative data was from interviewing operators and working alongside them in the existing calibration station while taking notes.

2.1 Literature Study

As stated previously the literature study was conducted to find information and data regarding perception sensors and methods for calibration of them. The strategy for the literature search was to use “string” that are highly relevant for the area of research. Some examples of strings that were used are the following: “Calibration of Radar, LiDAR, camera sensors”, “New Radar, LiDAR, camera calibration methods” and “advancements in Radar, LiDAR and camera” as these were found to be highly relevant for the research.

Before choosing to use the source as a reference question such as “why should the source be trusted”, “What is the topic” and “When was it published” were considered to evaluate the source’s credibility. Chalmers library was used throughout the research as the database as it was seen as trustworthy as it has an academic reputation to adhere to and it provides access to peer-reviewed publications. The literature search strategy therefore followed these three steps. Step 1 using search “strings” as the ones given in the examples to find potential articles and studies. Step 2 filtering out articles and studies which was not found relevant or too old (published before 2015). This date was set to get as new information as possible while at the same time having a large number of articles and studies to draw information from. Step 3 evaluating the articles and studies credibility using the previously stated questions but also by having internal group discussions with supervisors about the findings. These three steps were used to find each examined article or study and to filter out irrelevant ones.

2.2 Current State Analysis

While gathering the qualitative and observational data a current state analysis was performed, following Volvos internal structure for this method. This method utilizes the following structure: gather data regarding equipment, systems and layout, identify strengths and weaknesses at the station, time analysis of the entire process, and acquire operator inputs. This was done to help understand the current procedures when calibrating the perception sensors on the truck and to help pinpoint areas of potential improvement on the station. Doing this helps facilitating the conceptualization in further stages of the research as the analysis gives a clear understanding of how the current station functions. A current state analysis is a management strategy which evaluates the current process.

While acquiring operator inputs interviews were conducted while working alongside them in the station. Answers were discussed and then written down. The specific questions that were asked can be found in Appendix 1.5.

2.3 Concept Creation

After both the qualitative data from the current state analysis and quantitative data from the literature study had been gathered, concepts of a standalone calibration station were created. These concepts were created using the following structure. The first step that was carried out when it comes to creating overall system concepts for the entire station was to evaluate all the methods that can be used separately for calibration of LiDAR, Radar, camera stitching as well as camera recognition. The filtering was done by applying Kesselring matrices on a “method-level” where all methods are weighted in accordance with a set of criteria and then compared to one another based on the total score. The set of criteria and its associated weight differs depending on its level of importance and area of application (low or high-volume factory). The weighting is on the scale from one to five, with five indicating the maximum level of importance. A short explanation of each criterion and its associated weight will be presented in an upcoming sub-section. The best methods are merged for entire concepts by using Morphological matrices. These concepts are then screened using Elimination matrices which eliminated some of the concepts. To get a final concept for both high and low-volume factories the remaining concepts were screened once more with Kesselring matrices. The final concepts were then fleshed out and presented.

2.4 Tools

In the following sub-section, the tools utilized in the concept generation and evaluation will be presented. These are scientific methods mentioned by *Ulrich* in the book *Product design and development* [4].

2.4.1 Kesselring Matrix

A Kesselring matrix is a scientific method very similar to a weighted decision-making matrix and it's a tool used to evaluate and study different alternatives based on a set list of factors or criteria. The factors or criterion are often of high importance in the decision-making process. Each criterion has its associated weight which reflects its grade of importance. Then each method or concept gets a rating depending on the level of fulfillment of the specific criteria. The rating and the weight are then multiplied with each other giving a fulfillment score for the specific option and criteria. The sum of all the fulfillment scores is then gathered to obtain a total score for the option. The total score of the different options are then used as a mechanism to compare them against each other.

A disadvantage when using this method is that the weighting is based on guesses and are not based on quantitative measurements. The criterions used are presented and explained below.

Maximize Target Tolerance

This criterion is directly translating to both into the tolerance on where the target should be placed and how precise the target must be for the calibration procedure to be executed. Since small tolerances are associated with high cost and complexity, maximizing this would be favorable. Therefore, the level of importance of this is moderate in both high and low volume factories.

Maximize Accuracy / Performance

This criterion relates to overall accuracy and system performance of the perception sensors post

calibration. The criteria on this are non-negotiable since accuracy is key for reliable target detection. Therefore, the weighting is high for both low and high-volume factories.

Minimize Process Time

Minimize process time, as the name suggest, means minimizing the time it takes for the whole calibration to be performed. In the case of a high-volume factory, time is a very import factor and is indirectly associated with cost. While in a low volume factory, time is not as an important factor. Due to this the importance of this criteria is deemed to be high in the case of high-volume factory and low in the case of the low-volume factory.

Minimize Investment

Rather than the referring to an exact investment calculation this criterion refers to an estimate of the cost of installing the equipment needed for the method to perform the calibration process. In the case of a high-volume factory, it is assumed that a larger investment came be allocated for the station than in the case of a low-volume factory. Therefore, in a high-volume factory the weight is of a moderate level and in a low volume it is weight highly.

Minimize Footprint

This criterion is referring to the area which is needed for the method to be able to perform as intended. In a high-volume factory a larger area for a station is not as impact full as in a low-volume factory. Therefore, it is weighted as moderate in the case of a high -volume factory and high in a low-volume one.

Minimize Manning

Minimize manning means to have as few operators in and around the station as possible. This is weighted as low on both high and low volume factories.

Minimize Maintenance

As maintenance is highly linked to process time as doing maintenance on the equipment in the station means that no work can while it is being done. Therefore, minimizing maintenance in a high-volume factory it is weighted highly and in a low-volume factory it is weighted moderately.

Minimize Complexity

In a high-volume factory, it is assumed that there are more resources to handle complex methods. While in low-volume factories it is also assumed that these resources are more limited. Therefore, the weight of the criterion is high in a low-volume factory and low in a high-volume factory.

Maximize Robustness

Robustness is related to the ability of the methods to handle variability in operation conditions, environment conditions and the human factor. This is seen as very important in any manufacturing site and is therefore, weighted highly in both high and low volume factories.

Maximize Scalability

The criterion, “maximize scalability” refers to what degree the method enables testing of a growing number of sensors using the approach. Included in the criterion is also if the method compromises the performance or requires substantial modifications to the station when more sensors are added to the product. Both in the case of high and low volume factories this is very important, therefore, it is weighted highly in both cases.

Maximize Interoperability

This criterion relates to the ability of the method to perform calibration in conjunction with other

methods without causing issues related to performance or creating conflicts. This is of great importance as the field of perception sensors is moving forward at a rapid pace which in turn can lead to new methods being needed. Therefore, it is weighted highly in both low and high-volume factories.

2.4.2 Morphological Matrix

Morphological matrix is a scientific method used to generate, explore, and create potential solutions. This method suited for exploring different combinations or configurations that could solve the different functions. With the solutions of each function being listed it enables discovery of synergy between the combinations. Further, it also helps to avoid potential pairs of sub-solutions. In general Morphological matrices serve as a tool to support free and creative thinking when exploring diverse combinations for solving a problem.

2.4.3 Elimination Matrix

Elimination matrices are a method used when a lot of concepts have been created. Which can then be used to screen out concepts who are not worthy of further investigation or should be eliminated because of uncertainties. To identify which concepts who are not worthy or have uncertainties a set of criteria is once again used. The list of criteria can be seen in the elimination matrix in Appendix A.4.

3 Theory

This chapter aims to provide readers with essential background information on Radar, LiDAR, camera technologies, which is relevant to the topic. The section will act as a foundation for understanding subsequent chapters concerning calibration methods for each of these sensor types.

3.1 Radar

This chapter, together with its subsequent sub-sections, will focus on the operational principles underlying modern Radar sensor technology, as well as the recent advancements in this field. However, before that a short description of what a Radar sensor is will be given. A Radar sensor is a device which transforms microwave signals into electrical signals. Unlike other sensors Radar sensors are not affected by darkness or light and they can detect obstructions such as glass [5].

3.1.1 Working Principle for Radar

The early Radar systems for the automotive industry used a variety of frequencies but most of them operated at or around 24 GHz. This was due to them being seen as less complicated to design and manufacture. At the same time a large amount of research was dedicated to systems which operated at 77 GHz. The research was done as there was a major advantage in available bandwidth which opens the possibility of using FMCW (Frequency Modulated Continuous Wave) scheme. The advantage of a FMCW Radar is that its sensitivity increases with the available bandwidth [6].

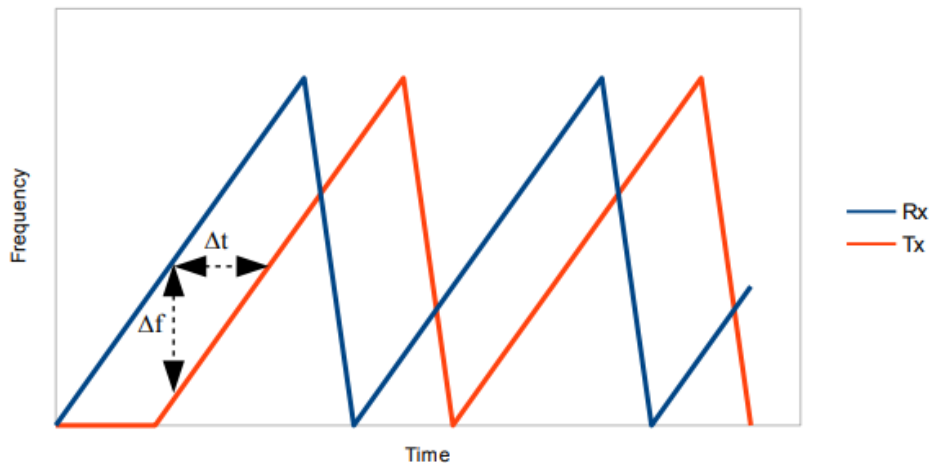


Figure 2 - FMCW Radar operation

Figure 2 above shows how a FMCW Radar transmits a signal which varies in frequency with time. At the same time the received signal which will also vary in frequency but delayed this gives a single low IF (intermediate frequency). The IF is directly related to the distance to the target and can be calculated relatively simple signal processing techniques. This is done with relative low-cost DSP (Digital Signal Processing chips). Other advantages with 77GHz are that a Radar operating at it is unaffected by weather and has a small antenna which means it is easy to integrate into vehicles [6].

Alongside FMCW Radar there is also CW (continuous wave) Doppler Radar sensors which uses continuous wave signals to detect objects. CW Doppler sensor measures the doppler shift of the reflected signal to determine the targets velocity. The CW Dopplers flaw is that it does not work as good as FMCW Radars over long distances. Further information on CW doppler Radar in the automotive industry will be presented in the next sub-section [7].

There were however some complications in the beginning when automotive Radars operating at 77 GHz were implemented. These were that the equipment was bulky, heavy, and expensive which made them more suited for either high end cars or heavy equipment such as trucks. Commercialization started when MMICs (Monolithic microwave integrated circuit) which operated at the right frequency became available which allowed the minimization of the Radar system for the automobile industry. The pursuit of MMICs based systems was initiated by two EU framework projects which were Dense traffic and RadarNet launched in 2011 and 2010 respectively [8]. The dense traffic project was aimed at developing a forward-looking Radar sensor. Which would enable a cruise control for traffic jams and function for warning the driver of a collision if the current velocity were to be maintained. The RadarNet project was aimed to develop new technologies for improving accuracy and reliability of Radar-based sensor systems.

3.1.2 Modern Radar Sensor Landscape

Modern Radar sensor still uses the previously mentioned 77 GHz system as they have relatively small antennas which are easy to interrogate onto an automobile. The difficulty with integrating the Radar sensor is the sensors beam as there are many requirements on the field of view the sensor needs to have. By design cars does not have a good cross section from the rear this means the beam of the Radar sensor governing the cruise control needs to be concentrated where the most metal is present in the rear of most cars. In the same instance the Radar can't react to any other vehicle than the one it is approaching, drain covers, manholes, fences, or lamppost. This results in that it is very important that the beam is correct as otherwise many problems may occur.

The capability to produce and fabricate 77 GHz Radar sensors using silicon is a significant technological advancement that has gained widespread adoption in Radar sensor technology. This is because it has resulted in single chip Radar solutions being possible which in turn lead to Radar sensor being even more commercially available for ordinary cars and other applications both in industry and domestic. [9] The Radar sensors attributes combined with their relative low cost is what makes them so widely used in modern car manufacturing. As stated, before Radar sensor are often used in vehicles for cruise control but can also be used to implement functions such as blind spot detection and autonomous emergency breaking [10].

As previously mentioned, the CW doppler Radars are not as widely used in the automobile industry as the FMCW as they do not have the required working range for applications such as cruise control. There is, however, some case where CW doppler Radars are used for applications such as collision avoidance and speedometers.

3.1.3 Advancements in Radar Sensor Technology

An advancement in Radar technology is 4D Radar sensor which is also called “four-dimensional” Radar sensor. The difference between 4D Radar sensor and regular Radar sensor is that the 4d Radars also gives information about objects altitude and its movement over time. These capabilities are useful when tracking the trajectory of an object. [11] Using Bosch Radar sensors as an example there are several differences between their regular Radar sensor and their premium 4D Radar sensor. The first difference is the size of the two sensors where the premium sensor having a five times larger volume then their regular Radar sensor. Other differences are their power consumption, detection range and accuracy. [12] [13] Other smaller but as important advances that being made in Radar sensor technology are better antenna technology, higher transmit power and digital beamforming.

Using the mobile 5G network for Radar sensing may be a more distant prospect than other Radar sensor advancements however, its implementation could have a significant impact. Enabling automobile Radar sensors to receive signals through the 5G network. This would enable automobiles to interpret signals from other devices, such as mobile phones and structures. To make this viable the 5G network first needs to be expanded and widely used. the second challenge is to develop an algorithm that can distinguish between signals that are useful for the car and those that are not. While there are other challenges, these two are currently the most pressing [14].

Machine learning has made it possible for Radar sensor manufacturers to design smaller antennas for their Radar sensors. Recent advances in larger memory sizes in computers and computing power have made it more likely to succeed in training a machine learning algorithm such as a neural network. The industry has been affected such that manufacturers now have more choices to optimize their antennas, whereas previously they had to simulate each optimization which could take several days depending on the computer used for the simulation. This has led to a quicker design face of the antennas and the Radar sensors [15].

3.2 LiDAR

LiDAR (light detection and ranging) technology, also known as Laser-Radar, is one of the newer perception sensor technologies to be applied in vehicles. This section will aim to provide some insight into the different types of LiDAR sensors but also go through the general working principles for LiDAR and how it’s used.

3.2.1 Working Principles for LiDAR

LiDAR technology operates on similar principles as Radar technology. It measures the distance to an object based on the round-trip principle which suggest measuring the time it takes for a wave to travel from a point of origin to an object, bounce off the object, and return to be picked up/measured by the sensor. However, the difference is that instead of emitting a high-frequency electromagnetic wave, as in the case for Radar, LiDAR sensor emit a laser signal/wave [25] [26].

The signal/wave LiDAR sensors emit are typically infrared light in short laser pulses. Infrared light is invisible to the human eye. The sensors rapidly fire out a series of brief pulses, usually at

a rate of thousands per second. The light pulses then return to the sensor after bouncing off objects within the sensor's field of view. The returning signal is what enables for calculation of the distance to the object by measurement of the time it takes. This type of data is usually referred to as point-cloud data. The typical operational frequency range for LiDAR sensors in the automotive industry is between 850 nanometers and 1550 nanometers, which corresponds to a frequency range of approximately 190 THz to 350 THz [27]. Figure 3 below is used to illustrate the difference in operational frequencies between Radar and LiDAR.

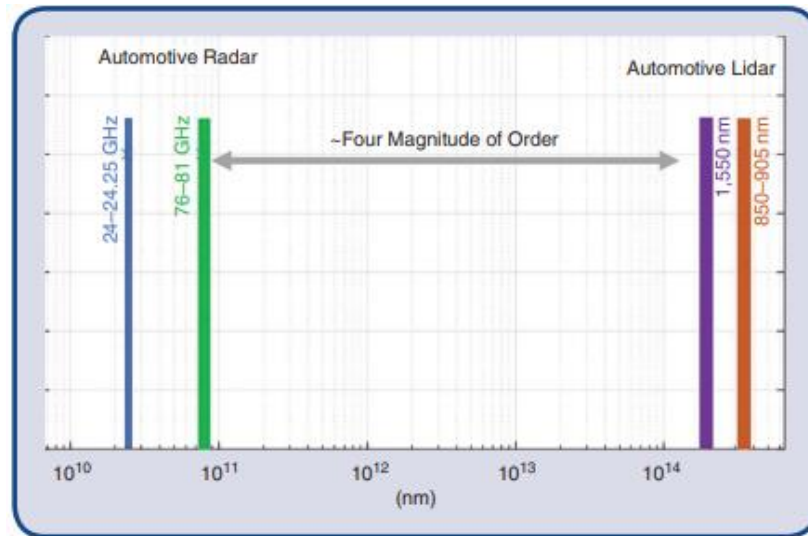


Figure 3 - Difference in operational frequencies [27]

Repeating this process many times per second while scanning the laser across a wide field of view allows the LiDAR sensor to create a detailed 3D map of the surrounding environment. The 3D map/point cloud can further be utilized in the case of autonomous vehicles for detection and navigation around obstacles. See Figure 4 below for illustration of a LiDAR point cloud.



Figure 4 – LiDAR point cloud illustration

3.2.2 Types of LiDAR

Generally, there are two categories of LiDAR sensors that are developed and utilized for automotive applications. These are Time of flight LiDAR and Coherent Frequency Modulated Continuous Wave (FMCW) LiDAR. Time of Flight LiDAR can further be separated into the categories of Scanning LiDAR and Flash LiDAR, where each has slightly different operational principles. A breakdown of technologies classes under LiDAR can be seen below.

- LiDAR technologies
 - Time of flight (ToF) LiDAR
 - Scanning LiDAR
 - Mechanical scanning LiDAR
 - Solid state scanning LiDAR
 - Microelectromechanical systems (MEMS) mirror LiDAR
 - Optical Phase Arrays (OPA) LiDAR
 - Flash LiDAR
 - Coherent Frequency Modulated Continuous Wave (FMCW) LiDAR

3.2.2.1 Time of Flight Scanning LiDAR

As previously touched upon, ToF LiDAR measures the round-trip travel time of photons from the laser to a target and back. By doing this the distance can be calculated based on the time of flight and thereafter construct a 3D map or point cloud of the object the laser encounters on its path [25].

The most commonly used scanning LiDAR is the Velodyne rotation scanner HDL-64E, which uses 64 laser-detector pairs to scan 64 separate planes. This translates to an angle coverage of 26.9°. It further spins 360° at a frequency of 10-30 Hz and can detect objects up to 120 meters away [28].

While mechanical scanning lasers like the Velodyne are widely used, they are expensive and have moving parts that can fail in certain driving environments, such as when harsh weather conditions are present. However, to make LiDAR more affordable and reliable, researchers are developing and investigating solid-state designs that include no moving parts. Two common approaches are LiDAR sensors that utilize either MEMS scanning mirrors or optical phase arrays (OPA) [28].

MEMS scanning mirrors utilize miniature, lightweight mirrors that are able to scan the entire field of view (FOV), in a fraction of a second. They are further suitable for scaling down price through large volume production and can dynamically adjust their scan pattern to focus on objects of particular interest. However, they have a limited angular field of view and can only scan in two dimensions, making multiple units needed for generation of a complete 360° view of the surrounding [27] [28]. Figure 5 illustrates the basic principles of the MEMS scanning mirrors.

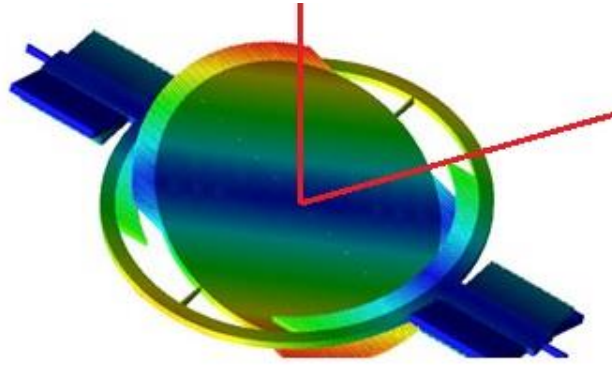


Figure 5 - MEMS scanning mirror principles

OPA LiDAR on the other hand have a “no-moving parts” design that promises excellent reliability. They consist of a one-dimensional array of optical elements that can re-emit incident light and steer the beam to any particular direction in one plane. However, they are currently the least developed technology and have not yet been tested on any meaningful scale [28] [29].

3.2.2.2 Time of Flight Flash LiDAR

Time of flight flash LiDAR is a solid state technology that works differently than the previously described scanning LiDAR. The flash LiDAR functions similarly to a flash camera. Rather than scanning the environment, it uses a laser beam that is expanded to illuminate the entire scene in a series of 2D or 3D flashes. The results in the creation of ToF point cloud that can be constructed by a one horizontal plane at a time or the entire 3D point cloud in one flash. An advantage when comparing this technology to that used in scanning LiDARs is that it eliminates the timing issues that may arise due to rapid changes in the measured target [28] [30].

The detector present in a flash LiDAR is usually a CMOS array or another 1D or 2D array of avalanche photodiodes (APDs) located on a focal plane of the detection optics. Each sensing element of the array measures the ToF to the corresponding scene element images on the particular sensing element, instead of light intensity. This allows it to measure the distance in real-time [28].

However, flash LiDAR usually have a limited range. The range usually goes up to a few tens of meters, due to limitations when it comes to the laser power. The range limit is also connected to laser beam’s expansion to cover the entire scene or at least one horizontal plane at a time. However, companies are currently working on technologies that would allow for an increase when it comes to both power density and range [28].

The solid state and no moving parts design present in flash LiDARs, make them a promising candidate for application in a variety of different fields. Autonomous vehicles, robotics and industrial automation are all example of fields that could potentially benefit from flash LiDARs ability to give reliable real-time information.

3.2.2.3 Coherent Frequency Modulated Continuous Wave LiDAR

Coherent frequency modulated continuous wave LiDAR is generally a more complex type of LiDAR, in comparison to previously mentioned technology. It allows for both the detection of distance and speed/velocity of an object in focus. Its operational principles are very similar to those of the FMCW Radar, where a continuously emitted wave is increased linearly from a base frequency to a maximum frequency. Subsequently, it is then decreased back to the base frequency over some time period. By doing this the two beat frequencies, that are produced by the interference of the emitted and reflected waves, can be measured. This opens up the opportunity for both the distance and the velocity of the object to be determined [25] [28] .

When comparing the FMCW LiDAR technology to the slightly simpler ToF LiDAR technologies, one immediate advantage is that of its immunity to ambient light. Ambient light can both be that of sunlight or just laser beams from other LiDAR units. However, this approach does have its own downsides. It for example requires a lot more computer power to be allocated to ensure proper functionality when generating point clouds. It further also has a different set of requirements on the laser source itself, in comparison to the ToF LiDARs [28].

There are, however, attempts being made from companies in developing FMCW LiDARs that are suitable for automotive related purposes in general.

3.3 Camera

This chapter as the two before it will focus on the technology, the history and recent advances in the field. The difference is that the technology in focus will be camera sensor.

3.3.1 Working Principle for Camera

One of the first working principles of camera sensors were when metal-oxide semiconductors (MOS) was used in experiments to create a new type of imaging device. The result of these experiments became a large two-dimensional silicon array where light was focused with the help of a lens. The photons in the light would then knock electrons which could be read by a connected electrical circuit. The electrical circuit then transmitted to a location where the image could be reconstructed [38].

Not to long after the MOS the charged-coupled device (CCD) came out which made it possible to easily manipulate the charges inside silicon structures. This made it possible for the first image sensor to be invented as well as the first digital camera which both used the CCD method. CCD sensors use MOS capacitors and in each pixel's capacitor electrons are kept these are often called pixel's buckets. The image is still analog until the data is read in each of these bucket's row for row. The first CCDs only produced black and white images however, it didn't take long before it was discovered that by putting a blue, red or green filter over each pixel a colored image could be produced [38] [39].

3.3.2 Modern Camera Sensor Landscape

The most widely used technology behind modern camera sensors is Complementary Metal Oxide semiconductors (CMOS). The CCD method was used over a long period of time however,

CMOS has become more popular in recent years. This can be contributed to that CMOS are cheaper to manufacture and reads information pixel by pixel instead of row by row. CMOS has an array of photo-detecting pixels who produces charges when subjected to light. The charge in each individual pixel is then sent to location close to the array where it is assessed. Even though the technology which CMOS are based on was discovered nearly at the same time as CCD the CMOS had problems with signal noise which CCD did not. CMOS require lower voltages than CCD as each pixel gives a useful output which has been amplified which is also one of the reasons it has become more popular in recent years. [38]

Modern automobiles are often outfitted with multiple camera sensors for different functions. These functions can be giving the driver a bird's eye view when driving at slow pace or work in conjunction with a Radar sensor to enable ADAS. These camera sensors have different requirements on them regarding accuracy and sensitivity depending on their function. These requirements are linked to their function as some cameras are only used to give the driver a visual representation on what is going on around the automobile while others are used in safety functions. [40]

In the ADAS the camera sensor is used for visual recognition tasks such as traffic sign recognition, object detection and lane departure warning. The camera captures images which is then sent to the automobiles computer which has a computer vision algorithm which processes the images. The algorithm then identifies and tracks the different objects the camera has captured such as other vehicles or pedestrians. [40]

3.3.3 Advances in Camera Sensors Technology

A technology which can help camera sensors take a new step forward might be quantum camera sensors. Another field that has already adapted this technology to some degree is televisions where it is called different things depending on the manufacturer, but the most common name is "QLED". As when semiconductors material absorbs light and releases electrons the same process occurs when quantum dots (QD) are used. The difference is that the released electron can't roam as freely, this occurs as the QD is only a couple nanometers in diameter. This means that the light absorb into the quantum dot is tunable. Meaning the color can be adjusted to nearly any wavelength by choosing the right material and particle size. This also opens the possibility to choose the color of light from when the electron recombines. Quantum dots also absorbs light more efficiently than silicon making it possible to make thinner sensors. Lastly quantum dots also sensitive along a broader dynamic range from very low light to very bright. [41]

The impact this technology could have on camera sensors is that they would be much less impacted from the brightness of the environment.

4 Results

This chapter will first go through LiDAR, Radar and camera calibration. The presented information about each of them will both investigate the current state but also encompass research about the future state of each of these. Thereafter some key elements from the currently used calibration station are presented such as layout, time aspect and functional parameters. The section after this focuses on the formulation of the requirements for a station solely for calibration of the perception sensors. These requirements are then used to make the different criteria's that are used for ranking the calibration methods using a Kesselring matrix. The best ranked methods are then merged into full on station concepts by the usage of morphological matrices.

4.1 Radar Calibration

In an automobile the Radar sensors are often calibrated for offset. The reason for this is that the assembly process for automobiles has tolerances, which causes the sensor to be positioned in varying location depending on the specific automobile. The variation on location on the automobile will result in each sensor giving small differences in their values. The difference in value will come from the "Radar beam direction" being different from the automobiles driving vector. To calculate the difference the following equation can be used where ε is the difference in value (error), d being the distant the Radar has taken the value from and α being the misalignment angle.

$$\varepsilon = d * \tan (\alpha) \quad [16]$$

The outcome is therefore that the Radar sensor needs to be calibrated so that each sensor in any given automobile will give the same value if meet with the same event. To calibrate a sensor in a manufacturing setting one-point calibration is often used as the sensor will be placed with small offset. One-point calibration for Radar sensors is when the sensor takes a measurement in an environment where everything is known without the exact location of the sensor [17].

An example of this would be a Radar sensor that takes a measurement when a target is placed directly in front of it with, with a known distance if the sensor where to be placed in the nominal testing position. The Radar sensor then takes a measurement based on the round-trip principle. the round-trip principle is when the sensor sends out a signal and tracks the time from when the signal was sent and when the sensor picks up the signal again. The time from the round-trip measurement is then used for the sensor to calculate the differences between the reference values and the recorded values. The sensor then calculates it's offset based on the difference [18]. It is important to note that the placement of the automobile and sensor bracket in 3D space needs to be known for this type of calibration to be performed.

This is also the used method for calibrating Radar sensors at Volvo trucks which will be presented in the current state analysis further into the report. Figure 6 bellow shows a simplified version of the one-point calibration principle.

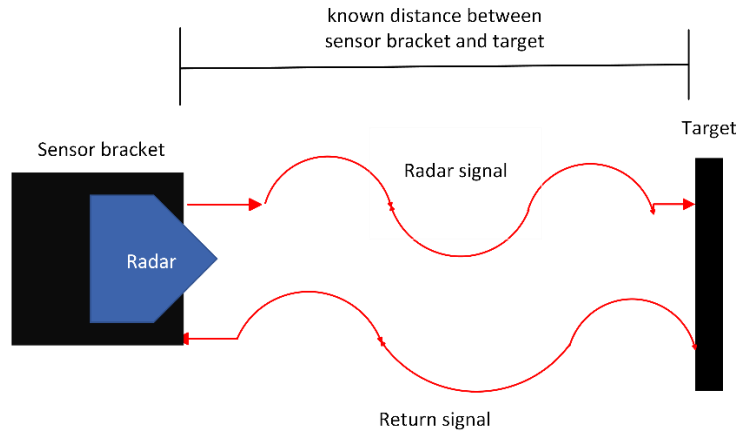


Figure 6 - Simplified version of the one-point calibration principle

There is also dynamic calibration which is done while the automobile is driving. For dynamic calibration to function the automobile needs to be driven at a specified velocity on track where it is alone for a lengthy amount of time. For the dynamic calibration to succeed the weather needs to be ideal (no mist, rain or snow). This means that dynamic calibration is not very fit for a high-volume production as the time it takes to perform is lengthy however, the investment is much lower as there is no need for a calibration station at the manufacturing site [19] [20].

4.1.1 Radar Calibration Methods

There are many calibration methods that are being investigated and researched at the moment this report is being written. Some of these methods will be brought up in this section of the report.

A new method to calibrate 4D-Radar that the company dSPACE is beginning to deploy, is a method where the calibration station is outfitted with parabolic reflectors to generate a plane wavefront. The idea is that the station would become a low-reflector chamber where the Radar sensors are calibrated with the help of a target simulator. The Radar sensor also needs to be able to rotate in both vertical and horizontal direction with high precision for it to work [21].

A new but novel Radar calibration technique is to calibrate the sensor online. As described in section 3.1.1 Radar sensors are built up by multiple MMIC and antennas working together, these components also have tolerances and variation which could lead to error contribution in the end. As of writing, online calibration can't replace the prevalent one-point calibration method rather it serves as a supplementary method. The online calibration is therefore done when the automobile is produced and out of the factory and used to compensate static errors. For the method to work several objects are needed and are then processed iteratively by a stochastic gradient descent. Performing online calibration increases the sensitivity of the sensor and increases the probability that the sensor detects "weaker targets" [22].

There is a "Shared field of view" method for Radar sensors which can calibrate for position and rotation. However, the technique has several requirements which needs to be meet for it to function. These requirements are that there is more than one Radar sensor, and that each sensor shares at least 45% of its field of view with another sensor. Using this method to calibrate

multiple Radar sensors who share their field of view with each other would result in a much shorter calibration process than if each sensor would be calibrated separately. The average accuracy this method delivered was $\pm 0,35^\circ$ in orientation and an average of $\pm 4\text{cm}$ in position. The “self-calibration” in this context means that with one calculation from one Radar sensor test the other Radar sensors can also be calibrated [23].

Modal wave expansion technique is a calibration method which can be used for Radar sensors which operate at a frequency over 100 GHz. When using Radar sensors who operate at this range the chance for calibration errors is higher when using the most common calibration method (one-point calibration). Therefore, using the Modal wave expansion technique for these types of Radar sensors becomes highly sought after as the technique eliminates the errors which can occur when the one-point method is used. The method finds the antenna displacement inside the sensor by taking measurements inside a confined space where absorbers are placed around the target and the sensor which can be seen in Figure 7 below. Figure 7 - Confined calibration space below. Similarly, to how dSPACE had when calibrating 4D Radar sensors. To determine the antennas, center a Modal wave expansion is calculated which is then used to calculate the antennas offset and calibrate the sensor [24].

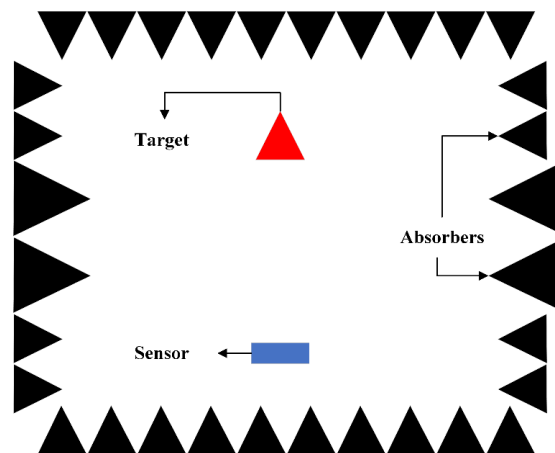


Figure 7 - Confined calibration space

4.2 LiDAR Calibration

Likewise of all other sensing systems, LiDAR required calibration in order to ensure a high degree of accuracy and reliability. In the case of LiDAR calibration proper calibration is critical in order to reach the required level of accuracy and precision of point cloud data that is generated. A sensor being incorrectly calibrated can result in the sensor picking up faulty reading when it comes to measurements, which in turn can have a negative impact on the system and overall vehicle performance.

In this sub-section, different methods for the calibration of LiDAR sensors will be presented. Potential advantages and disadvantages concerning each method will be brought forward as well. It is also of high importance to mention that a lot of the methods implemented for calibration of LiDAR equipment aim at simultaneously calibrating the accompanied camera equipment as well.

This is due to these two to a high degree being able to complement each other and enhance overall system performance in various applications. This in turn is defined as *sensor-fusion*.

4.2.1 Intrinsic Calibration

The Intrinsic parameters refer to the internal parameters within the LiDAR sensor. These parameters when it comes to LiDAR sensors can specifically related to things such as the distance between the focal point of the detector and the detector array, detector array angles, lens distortion, laser pulse rate and distortion, etc. However, since all this is in most cases all performed by the manufacturer of the LiDAR equipment it will not be of focus. Hence, it will be assumed that all intrinsic parameters are correctly calibrated before the LiDAR equipment is installed on the trucks.

4.2.2 Extrinsic Calibration

Extrinsic calibration, in this case, relates to the calibration of parameters that are not directly linked to a LiDAR sensor's internal characteristics, as mentioned in the previous sub-section. Extrinsic calibration rather involves determining the position and orientation of the LiDAR in relation to other objects that are picked up from within its' field of view. It can also relate to the positioning and rotation of the LiDAR sensor in relation to the vehicle it is places on. This calibration is typically done by for example by the automotive company ordering the LiDAR equipment, in order to ensure the accuracy and reliability of the gathered data.

In subsequent sub-section different approaches and techniques for extrinsic calibration will be presented.

4.2.2.1 Target-based Calibration Approaches

Target-based approaches/methods for calibration of LiDAR involve placing objects with a perfectly known geometry within the LiDARs field of view (FOV). The LiDAR sensor then measures the target/object which results in point-cloud data being generated. This newly measured point-cloud data is then compared to the expected point-cloud that would be generated by a perfectly calibrated LiDAR sensor. The comparison of data is what gives an indication whether a calibration is successful or not.

In the case of the gather point-cloud data being consistent with the expected expect point-cloud data of the known target/geometry, the calibration can be considered successful. However, if there are major discrepancies between the two data sets, this would indicate an error of the calibration of the sensor. By knowing the difference, the parameters of the sensor can further be adjusted in order for the error to be reduced and accuracy to be improved.

One commonly used target based approach is using sphere shaped targets [31] [32]. Another approach includes using a triangular pyramid shaped target [33]. Further research has also been done on implementing a plate with several holes in it, where the geometric relations between the holes is clearly known, picture illustrating the plate used in the study can be seen in Figure 8 below [34].



Figure 8 - Plate with holes used for calibration [34]

Another target-based approach is using plane objects. This is a method for calibration of multiple 3D LiDAR sensors all at once. For this approach it's necessary that three planes, independent of each other, are located within the field of view of all LiDAR sensors that are being calibrated, as indicated in Figure 9. Further, the planes that satisfy this condition can easily be found on objects such as the ground, walls, or columns [35]. This method specifically has great potential for implementation within a closed factory/production environment and the linked paper showcases those experiments performed in accordance with the proposed method generate more accurate extrinsic parameters than the more conventional methods previously mentioned.

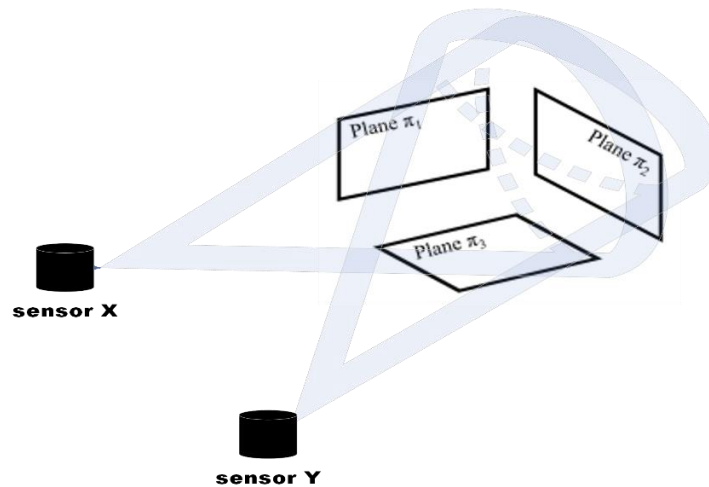


Figure 9 - Illustration of three independent planes within two LiDAR sensors FOV

Generally, what could be said for target-based extrinsic calibration is that it for most cases is a simple approach to testing the validity and accuracy of the generated point-cloud data. They do provide high precision in calibration due to the geometry of the targets being precisely known. However, the targets would have to be placed or mounted in multiple locations in relative to the sensors which can be tricky to do with high accuracy, hence, making it time consuming if having to be done manually.

4.2.2.2 Targetless Calibration Approaches

In contrast to target-based calibration, targetless approaches do not require any specialized setups of targets or patterns. Targetless approaches rely on gathering point-cloud data from natural features that are present in a static environment within the field of view of the sensors. Such natural features could include corners, surfaces, and edges. However, this approach is usually used to calibrate more than one sensor type at once such as simultaneously calibration of a camera. The previously mentioned features are detected and matched across for example the LiDAR and camera sensors which will help estimate and compute the position of these in relation to each other, enabling a fusion of their gathered data. Figure 10 is used to illustrates this.

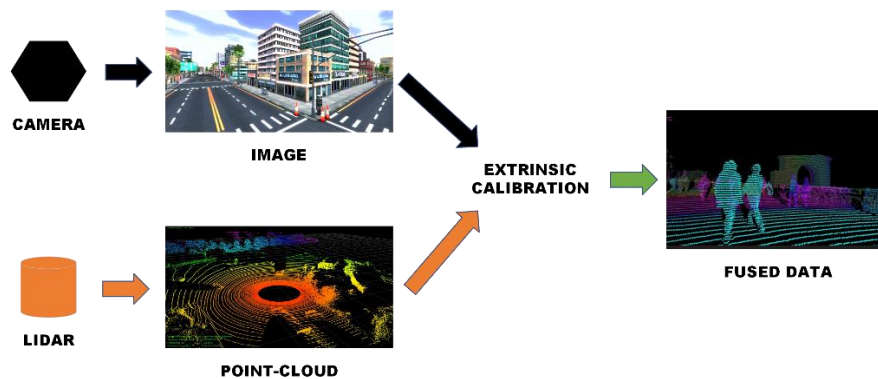


Figure 10 - Illustration of data fusion between LiDAR and Camera

The targetless approaches can be split up into two categories: *information theory based methods* and *feature based methods*. Their principles are however similar as previously described.

Information theory based methods aim to maximize the similarities between the set of data from the point-cloud generated by the LiDAR with the entire image brought forward by the camera sensor. These methods could be highly suitable for environments with a few distinct specific features, such as a closed off indoor manmade environments [32] [36]. Contrary to this feature-based methods are much more effective in environment that offers sufficient features. An example of such an environment would be an urban one [32] [37].

It's important to highlight, however, that these methods heavily rely on the internal algorithms that the sensors use for extraction of data directly from the scene/environment.

4.2.2.3 Dynamic Calibration Approaches

Dynamic calibration approaches can also be called *ego-motion-based methods*. As the name suggest they are based on calibration being performed in a dynamic environment. An example of such an environment would be when a vehicle is moving. However dynamic calibration usually requires a lot more processing power and computational resources in order to be performed properly, in comparison to approaches/methods brought forward in previous sub-sections. Reason for this is that these approaches require analysis of motion patterns of both the LiDAR and camera equipment simultaneously, in relation to each other. This can be a complex and computationally intensive task [32].

The amounts of data required in these operations is also significantly more if compared to data required in methods described in previous sub-sections. This is also a factor that contributes to an overall addition of time required for proper calibration to be performed.

However, what can be said generally for dynamic approaches is that they typically require significantly less of an investment in calibration equipment, in comparison to other methods that heavily rely on a setup of specialized targets. As a result of this, dynamic calibration methods can be particularly advantageous in certain scenarios where for example time is not a critical factor and cost considerations are of priority.

4.3 Camera Calibration

As Radar and LiDAR sensors camera sensors also needs to be calibrated to ensure reliability and accuracy to a high degree. Camera sensors have some key differences in the way they are calibrated and can mostly be divided into two categories these will be presented in the upcoming sections.

4.3.1 Object-based Calibration

In this category calibration techniques, which require object for calibration are included. The different methods in this category needs different types of objects some need very precise information of the object in 3D space. Methods with this approach often needs an expensive calibration arrangement and needs to see the object from a few different orientations. Therefore, methods to calibrate camera sensors by observing a pattern on a plane became more popular. As it was less expensive, and the pattern is easier to make than a precise 3D object [42].

The pattern can be different but is often in one these three categories snake board, checkerboard, or circle grids. An example on how a snake board pattern could look can be seen in Figure 11 bellow [43].



Figure 11 - Snake board pattern

Cameras used for the bird eye view feature that many new automobiles have are calibrated in a different way. As they will only be used for visuals and not recognition the cameras output only needs to be stitched together. The stitching can be done using a couple of different methods one being having lines on the floor around the automobile. Then the computer inside the automobile checks the different camera sensors around the automobile have overlapping and if they do, they are calibrated. This method is called feature-based calibration, important to note that these cameras that work together for the bird eye feature have fish-eye lenses [44]. A pattern to stitch together cameras can be seen in Figure 12 bellow. These patterns would be on each side of the vehicle.



Figure 12 - Pattern for stitching

Another method that can be used to stitch cameras together is stereo calibration. This method uses multiple cameras to take images of a scene from different angles. The images are then used to identify the external and internal differences the cameras have. The scene could also be the lines or patterns in Figure 12. This means it quite a similar method to feature-based calibration [45].

The Third method for stitching cameras together is dynamic calibration with the help of sensing algorithms. This method as some other dynamic methods is to be able to adjust the sensors values while it is in use. For cameras the need for an online platform where the values are sent and calculated for adjustment is needed. This method can also be used to calibrate LiDAR sensors and camera sensors together [46].

4.3.2 Self-calibration

Techniques in this category doesn't need any objects to calibrate the camera sensor. The cameras internal parameters will be estimated while the camera moves in a static scene. Meaning image information will solely be used to estimate the cameras parameters. There is a lot of parameters which needs to be estimated meaning that computational complexity will be increased greatly [42].

Regarding the computational complexity this could be the need to use a deep learning algorithm. The results of using these algorithms to calibrate camera sensors has not reached the same accuracy as object-based methods. However, the gap between them is getting smaller. For the camera to be calibrated by the deep learning algorithm measurements from the vehicle in motion is needed. Only using this method will not be enough to ensure that accuracy is high enough therefore the camera needs object-based calibration as well [47].

Another technique to self-calibrate cameras is to use videos to train the algorithm. This technique shows promising results where it can calibrate cameras to sub-pixel accuracy. The method, however, is more suited for recalibration where the automobile can use the video and the data it has already gathered [48].

4.4 Current State Analysis

The current state analysis is based on observations and questions asked to the operators working at the station. This made it possible to understand how the calibration process is currently done at the manufacturing plant at Tuve in Sweden. This sub-section of the report will go through an overview of the perception sensor placement on the truck, the layout of the station, the equipment used at the station, operators input and the time aspect in the station.

4.4.1 Overview of Perception Sensors and Their Locations on the Truck

The truck in its present-day configuration has a maximum of two perception sensors towards the front and two perception sensors modules at the sides. The two perception sensors modules at the sides can be further split up into four sensors with two being on each side of the truck. The approximate placement of the sensors and modules on the truck is illustrated in Figure 13 below.

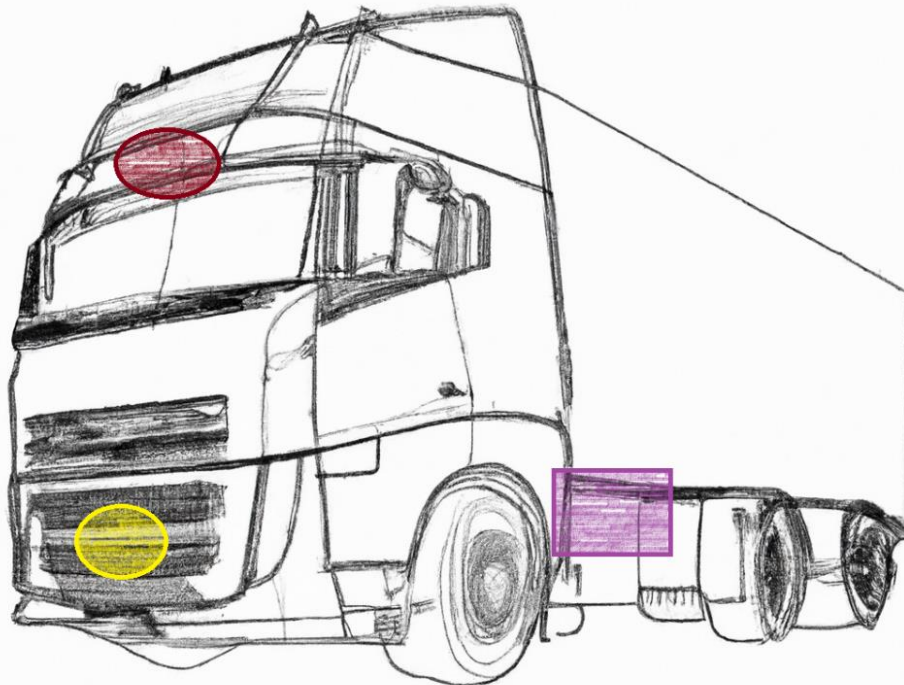


Figure 13 – Sensor and sensor module placements on the truck

The red ellipse in the figure marks the approximate location of the first perception sensor, which is the camera sensor or FLC. The Yellow ellipse marks the approximate location of the FLR sensor on the truck, which as observed is at the bottom front of the truck. The Purple rectangle marks the approximate location of the side-sensing Radar module that is on the side of the truck. On a fully equipped truck the same side-sensing Radar module can be found in the other side of the truck as well. The side-sensing Radar module, as previously mentioned, can be further split up into two Radar sensors. One of the sensors within each module faces towards the back end of the truck and the other looks towards the front.

4.4.2 Station Layout

The current station where the calibration process takes place is a combined station for wheel alignment and sensor calibration. The station consists of two lanes which are parallel to each other. While the equipment placement is almost identical across both lanes, there exists a distinction in the positioning of electrical cabinets. Having in mind the station is split up into two lanes, the cycle time can double in comparison to the average cycle time present at the main line. As of right now the designated cycle time is 12 minutes and 33 seconds for the station.

The layout of each lane from above is that of a rectangle where the length is approximately 17,5 meters and the width is 6 meters. Through the middle of the lane runs a service pit that has the depth of 1,6 meters, width of 1 meter and length of 12 meters. The service pit is mostly used for operations related to the wheel alignment of the truck; hence, focus will not be put here. The center point of the lane (origo) can be seen illustrated in the Figure 14 below where the two red lines meet in the right-hand side of the figure.

Directly situated on the ground plane (plane where the truck stands), along both sides of the lane, are robots equipped with several sensors. There are four of these robots present on a lane with the split being two on each side. All these robots are directly mounted on rails which allows them to freely move in the X direction, which is illustrated in Figure 14.

At the front end of the lane more equipment/a robot can be found that rolls out in front of the truck for calibration related purposes. This is a robot that consist of two plates/targets mounted on top of each other vertically, along a pole. This robot is similarly to the previously mentioned robots also mounted on rails, difference being they allow for movement in Y instead, as illustrated in Figure 14.

On each lane there are also four cobots (collaborative robots) situated along two rails at the height of 2,2 meters above the ground plane. Two cobots are on each rail and rails run alongside each side of the station approximately above the rails of the four previously mentioned robots. These cobots are also directly related to calibration related objectives.

Lastly, on each lane there are also electrical cabinets. However, the location of these cabinets differ, and the aspect of their location is not an important factor for the actual objectives that are being performed on the station. Hence, their exact placement/location will not be taken into great consideration.

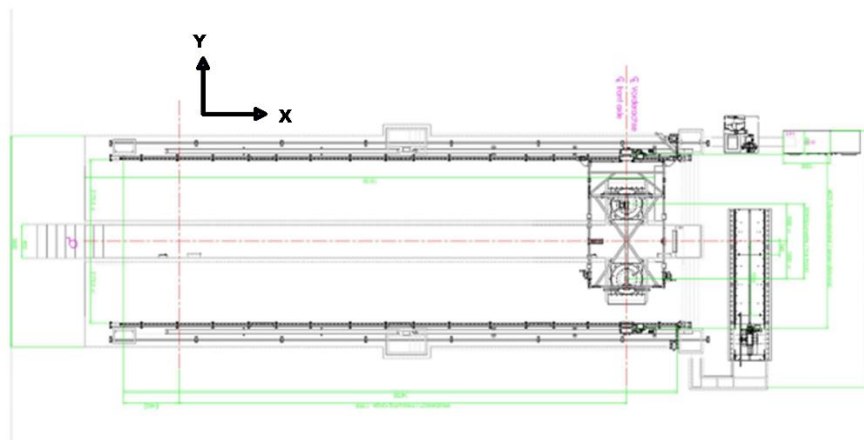


Figure 14 – Layout of the station

4.4.3 Physical Equipment Overview & Functions

This sub-section focuses on how the pieces of equipment can be generally grouped and what purpose each of these serves in solving the objectives present at the station.

4.4.3.1 Dürr Equipment

There are multiple pieces of equipment present on the station that are of Dürr origin and they are all directly involved in both the operations involved in the wheel alignment but also the operations involved in operation calibration of some of the sensors on the truck. The pieces of equipment, on each lane, that fall under the name Dürr are the following: the four robots mounted on the ground plane, a steering wheel balancer, the robot that rolls out in front of the truck, the two lights located at the front end of the lane.

Functions of each of these is discussed in the following sub-sections.

4.4.3.2 Dürr - Tire Scanner

These are four robots that move freely along two rails along both sides of the ground plane. As previously mentioned, there are four of these robots with two being on each side of the lane. These robots have a multitude of function and tasks that they have to perform. First one being that there are a crucial part in establishing where the center axis (center line) of the truck is located in 3D space. This is done by measuring lasers that each robot is equipped with in combination with the metal flags that are mentioned in a later sub-section. These robots are also a crucial part of the wheel alignment procedures as they take multiple measures on the wheels directly using the same lasers as in previously described task. A picture of one of these four robots can be seen in Figure 15 below.



Figure 15 – Tire scanner

4.4.3.3 Dürr - Steering Wheel Balancer

The steering wheel balancer is further a piece of equipment crucial for proper wheel alignment to be performed on the truck. It is directly mounted top of the steering wheel and its task is to help

perfect the relation between steering wheel movement and how it translates to movement of the turning axels of the truck. By utilizing both the screens discussed in the subsequent sub-section and an operator, the link between the servos and the steering wheel can be accurately calibrated and fine-tuned. A picture of the steering wheel balancer can be seen in Figure 16 below.

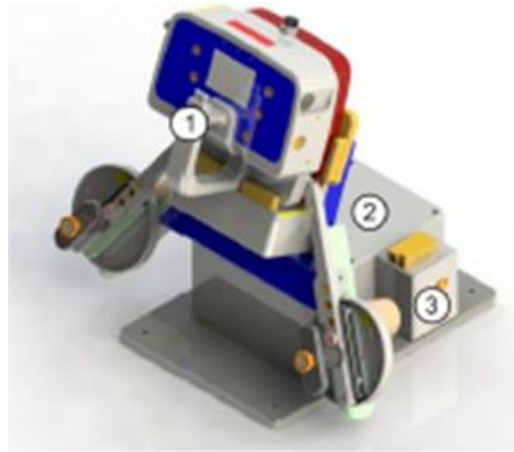


Figure 16 - Steering wheel balancer

4.4.3.4 Dürr - Tower with Targets

This robot is the one that drives up in front of the truck in order to perform calibration related tasks. The robot is on rail which allow in to situate itself in front of the truck but also retract when it's supposed to. The robot itself consist of two targets/screens vertically mounted on top of each other where each screen has a different purpose. The top target is for calibration of the FLC, and it has a "snake board" pattern painted on it. In the calibration process of the FLC, the camera relies on an internal system communication, which will be discussed in a subsequent sub-section, to determine the appearance of the pattern and report its detection to the system. The camera's feedback allows it to adjust its calibration settings to optimize its performance.

The target at the bottom doesn't have any patterns on it and it is fully blank. The purpose of this target is directly related to the calibration of the FLR. The calibration principles here are that the Radar is once again told through internal system communication that the target is located one meter directly in front of the Radar. The Radar then sends out a known signal, measures the time it takes for the signal to bounce off the target and return to the Radar, allowing the FLR to calibrate its measurements of range, velocity, and angle. The type of signal typically sent out by the Radar for this purpose is a pulse or a series of pulses.

A picture of the robot equipped with both the targets can be seen in Figure 17 below.



Figure 17 - Tower with targets

4.4.3.5 Dürr - Metal Flags/Extensions

The metal flags are piece of Dürr equipment that is directly screwed into the front of the truck itself. Their purpose is to act as an extension of the main frame of the truck and in doing so enabling the robots mention in section 2.3.1.1.1 to take measures of where the center axis is located in 3D space. The approximate mounting locations of these on the truck are illustrated in Figure 18 below. A picture of the two metal flags can be seen in Figure 19.



Figure 18 - Approximate mounting locations for metal flags

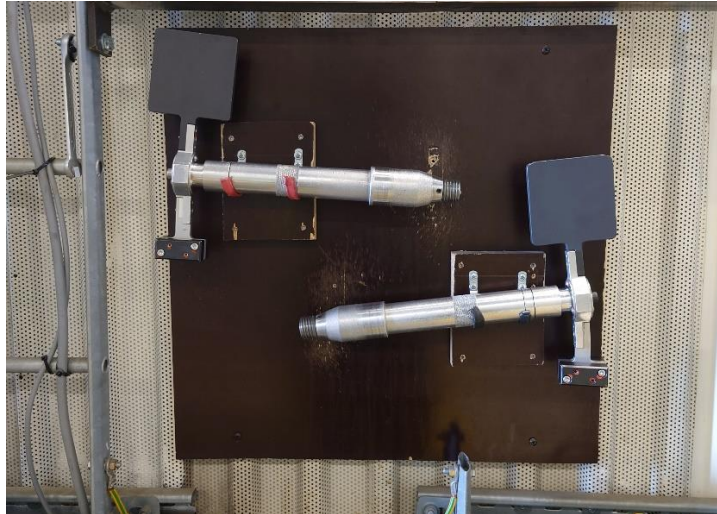


Figure 19 - Metal flags/extensions

4.4.3.6 Dürr – Lights

The lights present at the station is another piece of Dürr equipment. Their sole purpose is to create the most optimal light condition for when the FLC is calibrated using the target with the snake board pattern. Hence, why they are directly looking at it. A picture of the lights can be seen in the Figure 20 below.



Figure 20 – Lights used for creating good lighting conditions

4.4.3.7 Cobot Equipment

The equipment present on each lane, which falls under the Cobot category, are the 4 cobots that are mounted on rails on the height of 2,2 meters above the ground plane. As previously mentioned, the rails are in parallel to the lane on each side. If looked closer, each cobots consists

of a number of robotic joints which allows the cobot to move and articulate freely in space. At the end of the cobot there's a metal target/plate mounted. The purpose of the target is the exact same as the bottom one described in sub-section 3.7.3.4, with the difference being in sizing between these. The target in this case is significantly smaller than the Dürr equipment one.

To provide further elucidation, the function of the Cobot equipment is exclusively associated with the calibration of the sensors integrated within the truck. This is particularly applicable to the calibration of the side-sensing Radars.

The cobots receive, through internal system communication, information on where the side-sensing Radars are located in 3D-space. After receiving this information, the cobots are initiated and they move down and position themselves in perfect relation to the side-sensing Radars in order for the Radars to be properly calibrated.

A picture of a cobot can be seen in the Figure 21 below.



Figure 21 - Picture of a cobot (in safe position)

4.4.3.8 Remaining Pieces of Equipment

The remaining piece of equipment that doesn't fall under any of the above categories are the screens present on the station. There are 2 screens on each lane with one being above ground and the other one being in the service pit. The screens are utilized for displaying things such as operator instructions but also information whether calibration procedures are successful or not. These screens make it easy to follow along the procedures being executed at the station. A picture of a screen can be seen in the Figure 22 below.

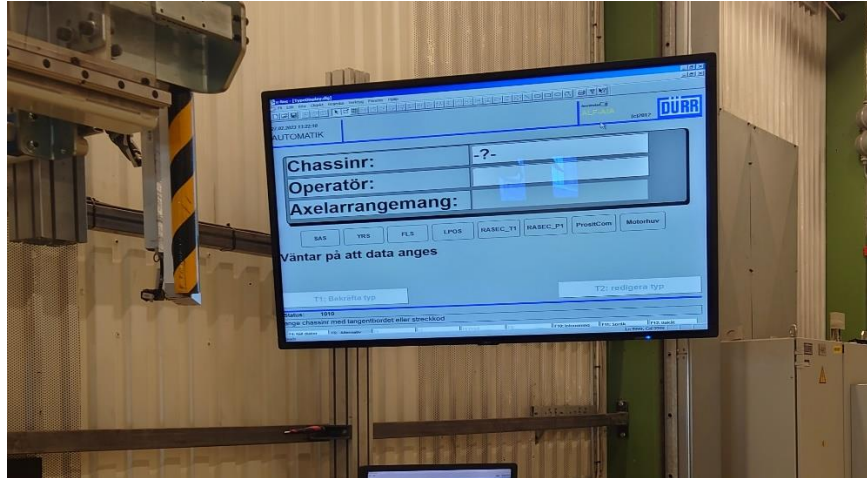


Figure 22 - Picture of the screen

4.4.4 Station Operations Related to Calibration of Perception Sensors

As emphasized in previous sections, the procedures done at the station can generally be split into two segments, where one is objectives needing to be done for proper wheel alignment and objectives needing to be done for proper calibration of the perception sensors. However, as previously mentioned, the focus of the analysis will solely be on the objectives needed for proper calibration of the perception sensors. Hence, the following operations described are only related to calibration.

4.4.4.1 Calibration of FLC & FLR

Calibration of FLC and FLR are both handled by the Dürr tower described in section 4.4.3.4 which works in accordance with the information that is supplied from the Dürr equipment described in section 4.4.3.2. How this information is transfer between the different systems will be described subsequently. The calibration of the FLC and FLR does not require any kind of operator intervention or action to be initiated. However, it does require for no operators or objects to be in vicinity or between the calibration targets and the truck, for it to be performed successfully.

The calibration procedure of these start with the calibration of the FLC which after it moves over to the calibration of the FLR.

4.4.4.2 Calibration of Side-sensing Radars

The calibration of the side-sensing Radars is solely handled by the cobot equipment that is described in section 4.4.3.7. The information in order for the equipment to execute the objectives is received through a system, Which is described in subsequent sections. However, in the case of the side-sending Radars direct operator initiation is required for the calibration procedure to start and further operator action is needed for the procedure to be finished, hence, giving the signals to the cobots to return to safe position. The reason for these safe measures are to avoid any type of collision with the truck, operators or other station equipment that can be present.

Calibration principles are described in previous sub-chapters. The calibration itself is performed sequentially but in pairs. First both the Radars that are forward facing are calibrated followed by the pairs that are backwards facing.

4.4.5 Systems Utilized in Station Operations

In order for the procedures involved in performing both wheel alignment and perception sensor calibration to be successful, six complex systems are used. These systems and their functions will not be discussed in detail due to confidentiality. Just an overview using placeholder names will be given in this section.

These six systems working in conjunction is necessary in order to ensure the accuracy and efficacy of the station. Further, the successful intercommunication between them is crucial for the station’s overall performance. Figure 23 below illustrates the communication channels present between the systems using placeholder names.

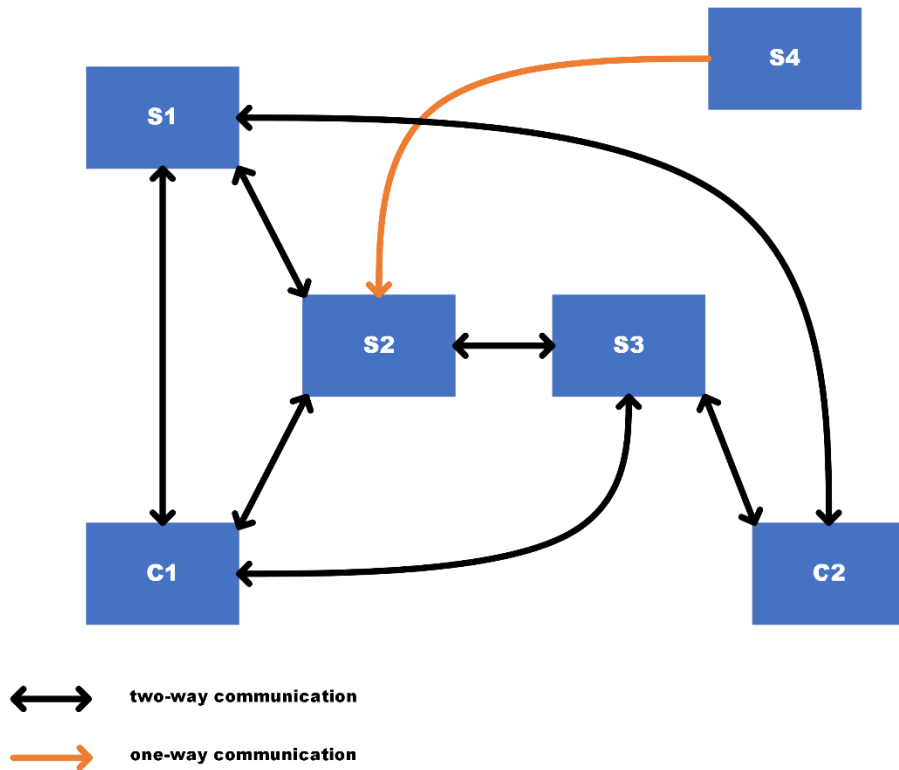


Figure 23 - Communication channels between the different systems (placeholder names)

S-Systems

System S1, S2, S3 and S4 each have different functions but can broadly be categorized as non-directive systems in terms of equipment guidance and movement. These systems are related to things such as calculation for target placement, step-by-step sequence execution, individual truck specification handling, etc.

C-Systems

System C1 and C2 are systems that are directly linked equipment movement or guidance and can

therefore be categorized as directive systems. These two systems are the ones that directly handle the mechanical movement in the targets that is needed for the perception sensor on the truck to be calibrated.

4.4.6 Observations & Inputs from Operators

To gain a comprehensive understanding of the station's processes, operator observations and inquiries were conducted in conjunction with the station's operations. Through this a fundamental understanding of the stations workings was established. Moreover, operators' perspective was taken into account and will be considered when conceptualizing the potential standalone station for calibration.

The following sub-sections will revolve around the strengths and weaknesses that are identified through the analysis and the interviewing of the operators. The operators will be referred as Operator A, B, C and D to keep them anonymous.

4.4.6.1 Stations' Strengths

4.4.6.1.1 Good Visualization of Instruction

When there are no mistakes or problem the screens give the operators good visualization on what step they are on as well as how the calibration is going. The screens also make use of the colors green and red to easily give instructions on when certain values are in the tolerance range. [49]

4.4.6.1.2 Work Rotation

The operators follow the truck for three stations which results in some variation in the work procedures instead of working at a single station doing the same movement and work for eight hours a day. [50] [49] [51]

4.4.6.1.3 Good Ergonomics

Most of the work in the station is within good range for ergonomics and there is not a lot of movements which are needed outside the "good/green" area of movements when working see Figure 24 . The only sequences which are not very ergonomically are when a protection is fastened under the truck and when one of the operators' hands or receives the steering wheel balancer.

Both these sequences results in the operators reaching over their head which is not good for ergonomics. [50] [52]

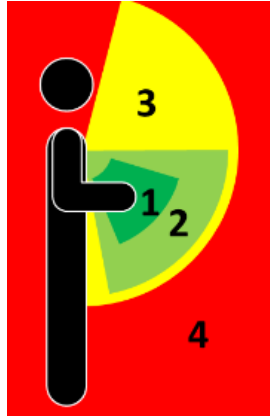


Figure 24 - Picture showcasing ergonomics areas

4.4.6.2 Stations' Weaknesses

4.4.6.2.1 Preparation Related Issues

Specifically, preparation related issues often occur when a Volvo trucks customer wants to make a change in their order specification, after the order is already sent out. However, the handling of the “special request” and update in specifications might be forgotten to be fed into the trucks internal system. In cases like these the truck will be built in accordance with the updates customer specifications, but the trucks’ internal system will not be aware of this, leading it to believe it looks a certain way when in reality it doesn’t. This information will wirelessly be transfer over. Calibration procedures will then be initiated based on this transferred information. Hence, the station might initiate its configuration based on for example where the trucks’ internal systems think certain sensors are located, when in reality the position is somewhere else. This would lead the station into misplacing the testing equipment in relation to the sensors. [49]

In cases like these it’s hard to forecast where exactly the calibration procedures will fail. This is due to it being hard to predict where in 3D-space the location of for example the side sensing Radars might shift to. Issues like these or related can often occur when the customer request a change in for example a tire change or a change in axle configuration or spacing on the truck. [51]

4.4.6.2.2 Assembly Related Issues

Assembly issues often have their origin from operations done on the main line. These are often tolerance related issues which, if not of very high severity, don’t have a big impact on the calibration of the perception sensors on the truck. They do however often impact the procedures which are related to wheel alignment which is also done at the station. [52] [50]

4.4.6.2.3 Shortage of Material

In cases where there is a scarcity of materials required for the station procedures, alternative materials may need to be used. This could result in additional steps being required at a later stage, which would increase the queue of trucks waiting to be tested. Such situations could impact the overall flow of the factory and may require additional resources to manage effectively. [51]

4.4.7 Time Aspects

This section will discuss the time aspect regarding the calibration process for the perception sensor. Everything that is produced in Tuve is logged in a data storage system this is done for traceability but can also be used when trying to find bottlenecks in the factory. The time aspect will be divided into three categories which are raw calibration time, system communication and mechanical time. Raw calibration time is the time it takes for the calculations to be done for the calibration process. The system communication time is the time which is required for the systems to confirm with each other that the different procedures are done correctly. Mechanical time is when the different targets are moving before the calibration process is done.

4.4.7.1 Raw Calibration

Using the data from the trucks that were produced during Q1 (first quarter) of 2023 the following values can be derived and seen in Figure 25 bellow.

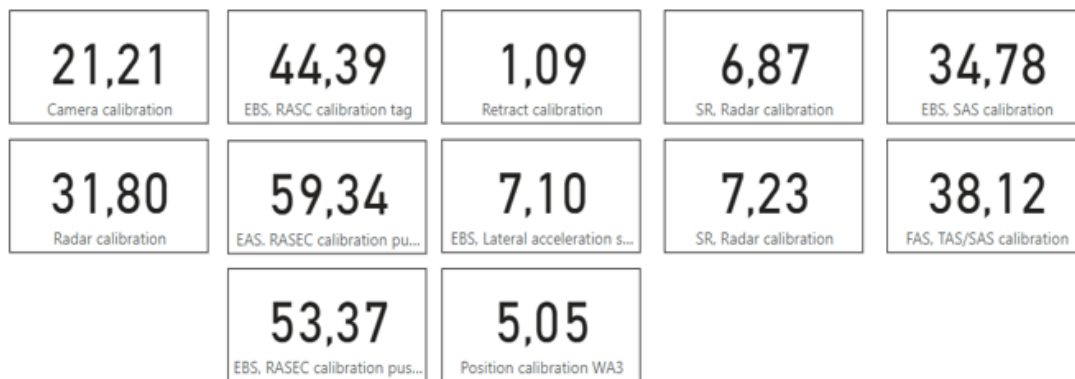


Figure 25 – Average time spent on calibration processes

These values represent the average time for the raw calibration time which means the system communication time, or the mechanical time is not included. The values used for the analysis are only of the calibration time for the perception sensors which means the following times camera calibration (FLC), Radar calibration (FLR) and the two times for SR, Radar calibration (side sensing Radar). With the analysis done of these averages, it became clear that the new generation of Radar sensors used in the side sensing sensors are much quicker to calibrate than the older one in the FLR. This can be derived from the side Radars only taking around seven seconds to calibrate while the front Radar taking around 30 seconds to calibrate. In total the raw calibration time for the FLR, FLC and the side sensing Radars is 67,11 seconds. The other time aspects are discussed in the subsequent sections.

4.4.7.2 Mechanical Time

The mechanical time it takes for the targets to move to their designated targets were identified by using a stopwatch. The stopwatch was used to measure four different movements two for the target which the FLR and FLC uses to calibrate them self and two for the cobots. The sampled times can be seen in Figure 26 bellow.

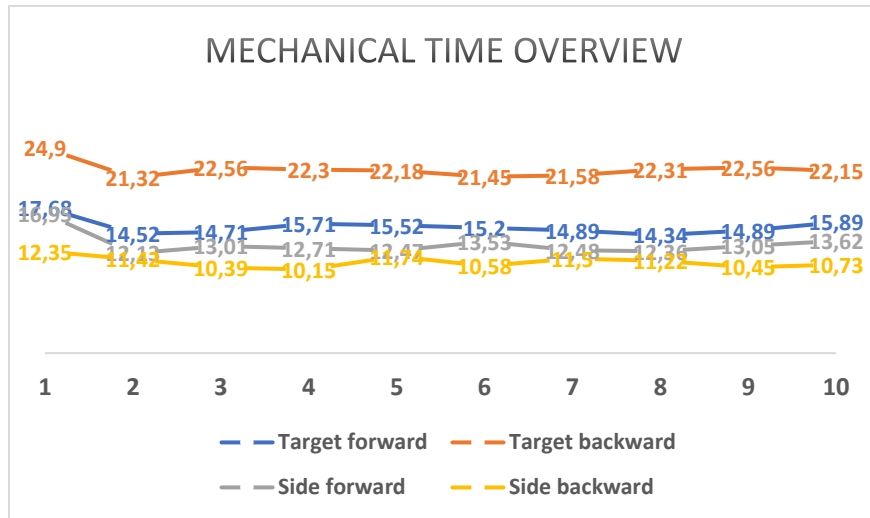


Figure 26 – Stopwatch times for mechanical movements

As can be seen in the figure two of the collected times was for moving forward (getting in position) and two were for backward (moving to the “home” position). Using these ten collected samples for each movement the average time it takes for the movements can be extracted and can be seen in Figure 27 bellow.

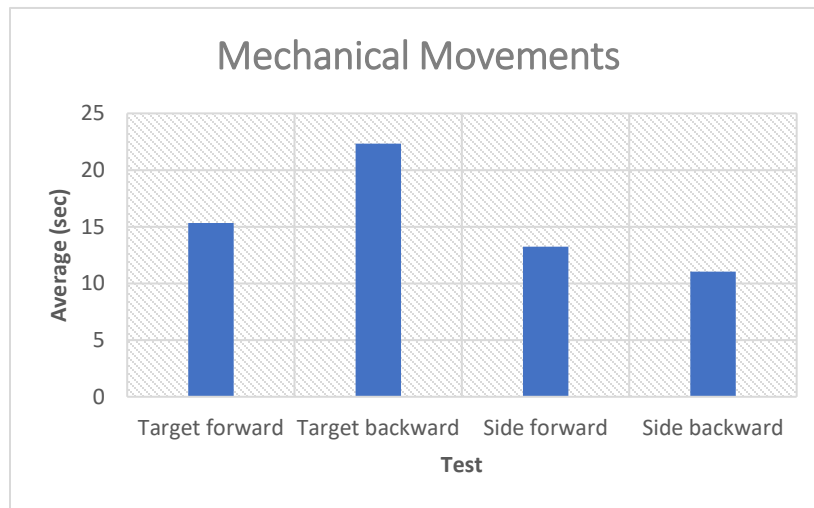


Figure 27 – Average times for mechanical movements

This means in average, in each cycle 61,95 seconds is spent on mechanical movements in contrast as discussed before the calibration for all the perception sensors takes 67,11 seconds each cycle. It can also be seen in Figure 27 that moving back the target for FLR and FLC is the mechanical movement that takes the longest time in average. However, in the current state of the station this is not a problem as the one of the operators needs to be present at the control station to initiate the next step in the process which is the calibration of the side sensors. Not all trucks have side sensors, which means often the operator is not standing ready at the control station when this sequence needs to be initiated. As a result, the extra time it takes for the target to move back is also used for the operator to move to the control station.

4.4.7.3 System Communication Time

To understand the time, it takes for the systems to communicate with each other during the calibration process the data storage system was used. The system stores all the data which is logged in it which means the time between sequences in it where the systems are communicating with each other can be analyzed. Using the logged time in the system for ten trucks the average time for the systems to communicate during the calibration process can be analyzed. The logged times for the system communication can be seen in Figure 28 below for FLR & FLC and the side sensing Radars.

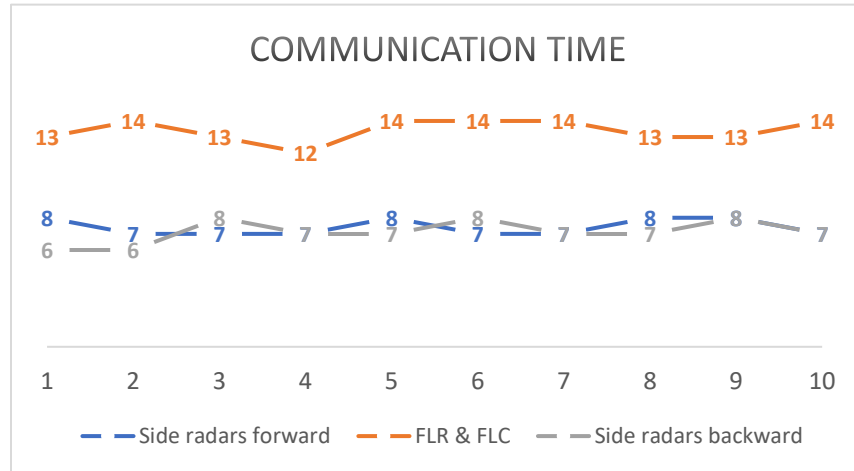


Figure 28 – Recorded times for system communication

It is important to take into consideration that FLR & FLC is one time but the communication between systems is initiated two times during this process. Therefore, the amount of time is twice the amount for FLR & FLC than it is for the side sensors. When analyzing the times for the side sensors in the data storage system it also became clear that there is another time aspect to consider. This aspect is concerning the time between the system giving the message that it has done all the procedures and that one of the operators confirms this by pressing a key. When further analysis was done into this aspect it showed that this time could vary between a couple of second to one to two minutes.

4.4.7.4 Time Breakdown

The summarization of the time aspects can be seen in Figure 29 below with each aspect on their own and the total time of the three aspects together. In total 156,96 seconds are spent solely on the aspect of calibrating the perception sensors in the station. Of the 156,96 seconds 61,95 seconds is spent on mechanical movements, 67,11 on calibration and 27,9 system communication.

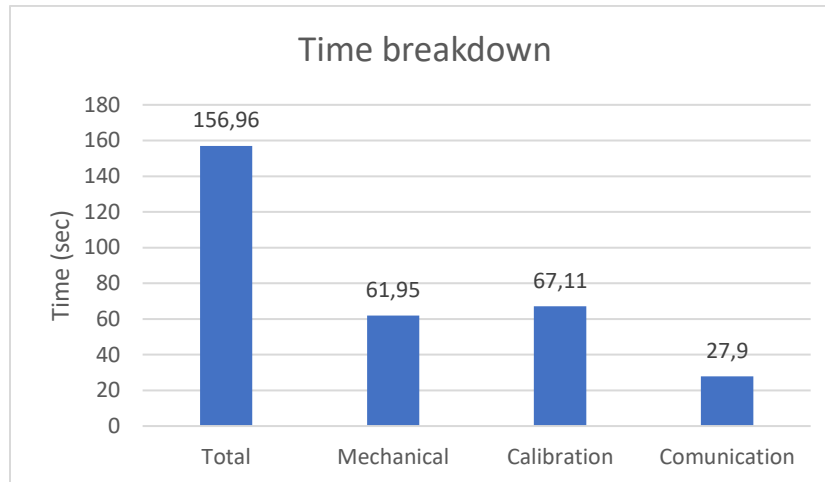


Figure 29 – Total time breakdown

With the time analysis complete the findings can be used for the forming new concepts for a standalone calibration station for perception sensors.

4.4.8 Station Analysis Results Related to Calibration

The AS-Is analysis revealed areas of strength and areas, related to calibration, where potential improvements could be implemented on the current day station to make it more adaptable at handling an increased number of sensors. It also helped identifying factors that need to be taken into account when creating new station concepts/proposals. These will be highlighted below.

Identified strengths

- Rail system is highly scalable and potentially allows for more cobots to be added directly on it
- The use of cobots allows for high reachability and sensor calibration in almost any location on the truck
- Calibration methods used are not excessively complex and could potentially be implemented in both a high- and low-volume factory
- The time it takes to solely perform the calibration of the sensors is not excessive
- Robust and precise process when calculating the truck's position in 3D-space

Identified areas of potential improvements

- Decreasing the number of systems present on the station
 - This could have a decreasing effect the overall system communication time, enabling more time to be allocated to the calibration itself
 - Would make it easier to troubleshoot and perform diagnostics in the case of an issue occurring
- Preferably use equipment from the same supplier enabling easier interoperability
- The target screens on the cobots have the potential for multifunctional use, including the calibration of the camera

- Decrease the number of inputs needed from operators or eliminate them in order to achieve a higher robustness in the process
- Enhancing the station's capability for calibration of LiDAR sensors added on to the truck in the future
- Enhancing the station's capability for stitching of camera sensors added on to the truck in the future

5 New Station Concepts

This subsection of the result chapter presents the creation, filtering, and evaluation of the different concepts.

5.1 Filtering Outcome

By the usage of Kesselring matrices some of the methods for calibration were filtered out depending on their area of application. The full Kesselring matrices can be viewed in APPENDIX A.2.

The surviving ones are the following

For high-volume factory:

- **LiDAR:** geometrical targets calibration, plane targets calibration and hole targets calibration
- **Radar:** one-point calibration and Shared FOV calibration
- **Camera recognition:** object based 3D calibration, object based 2D calibration and dynamic calibration
- **Camera stitching:** feature-based calibration and stereo calibration

For low-volume factory:

- **Lidar:** Ego-motion calibration, Feature-based calibration and geometrical targets calibration.
- **Radar:** One-point calibration and Dynamic calibration.
- **Camera recognition:** Object based 3D calibration, Object based 2D calibration and Dynamic calibration.
- **Camera stitching:** Feature-based calibration and Dynamic calibration.

5.2 Concept Generation

Based on the surviving calibration methods mentioned in the previous sub-section, two morphological matrices were created. One was for the high-volume factory setting/environment, and one was for the low-volume factory setting/environment. This allowed for synthesis of the different methods into complete station concepts which cover calibration of all the perception sensors on the truck. This resulted in five concepts being created for each of the two factory settings Both morphological matrices can be found under APPENDIX A.1.

Important to mention, however, is that not all permutations were looked into, as this would lead to 36 concepts having to be analyzed and created. Instead, the five generated concepts were based on possible synergies between methods while also trying to avoid conflicting factors between these. The five created concept for each factory settings are described in next-coming subsections.

5.2.1 High-volume Concept 1 (H1)

The first concept for high-volume factories would use the following methods for calibration.

- Geometrical targets for the calibration of the LiDARs
- One-point calibration for the Radars
- Object based 3D calibration for the camera recognition
- Feature-based calibration for the camera stitching

An idea concerning the potential layout of the station that incorporates all these calibration methods is illustrated in Figure 30 below.

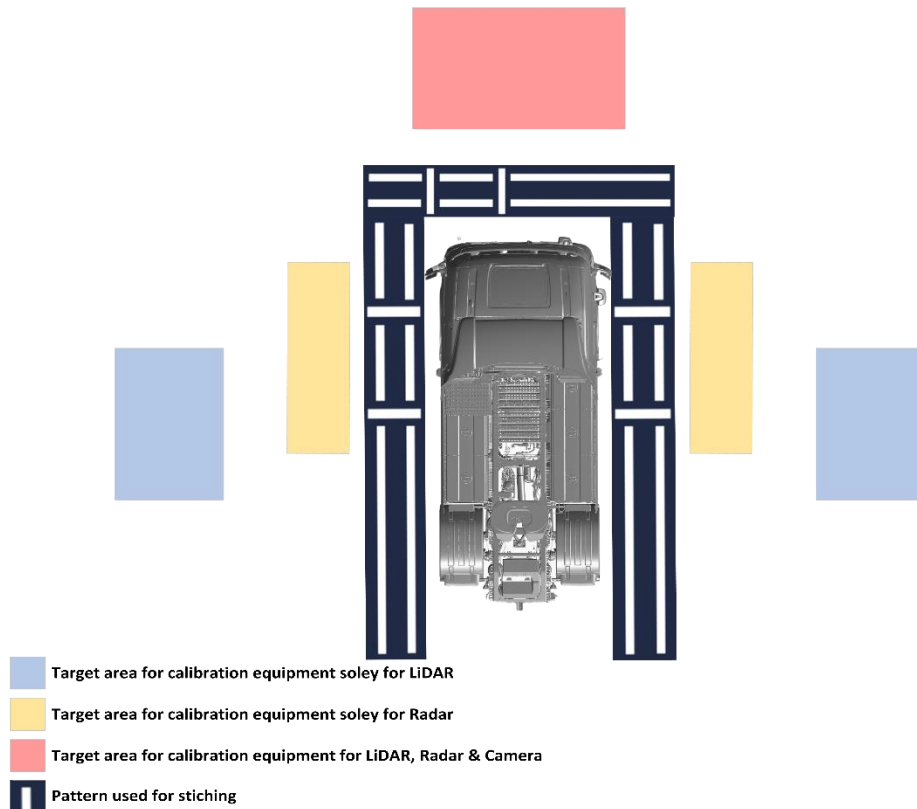


Figure 30 - Suggested layout for High-volume concept 1

Red-marked area illustrates the approximate location where target equipment can be placed for calibration of all three perception sensor types. The equipment in this area could be similar to the one found in the present-day station setup where a robot with screens attached to it is placed in front of the truck. The screens could hypothetically be minimized to one unit, that will be used to calibrate the Radar sensor that is in the front of the truck. However, the robot holding the screen could, for this concept, incorporate a 3D geometrical target such as a pyramid with a snake-board pattern printed on each side, that will be used for calibration of any LiDAR sensors that are aimed towards the front of the truck together with front-facing camera sensors. This target could be placed on the same shaft as the screen in order for it to be rolled out/placed in front of the truck at the same time. Placing it on the same shaft would also minimize the mechanical time compared to a new target needing to be rolled out separately.

The area marked in yellow illustrates where equipment can be placed solely for the calibration of the side-sensing Radars on the truck. The solution for this specific case can be very similar if not

the same as the present-day configuration. Having it the same as before would allow for full clearance of the station since the cobots can move up to a safe position. This would allow for the calibration of the any LiDARs placed alongside the side or edges of the truck, by installing calibration equipment in areas marked in blue, without any interferences or blocking pieces equipment. The calibration targets in the blue-marked areas could both be statically mounted on walls or the floor or mounted on a robot that would allow for small movements in order for variation of the truck to be taken into account.

The striped area is for the stitching of the camera sensors that can be placed in and around the truck.

For this concept to work the following requirement would have to be met:

- The trucks' position in 3D-space has to be set or measured somehow in order for calibration to be performed
- In the case of static targets for LiDAR calibration all expected variations in point cloud data have to be stored and used by a system at the station
- Target placement accuracy has to be guaranteed, along with ensuring high surface quality of the targets
- Stitching pattern has to be durable due to truck having to drive over it in when continuing onto the next station
- Target area in red has to be retractable in order for the truck to be allowed continuing onto the next station

5.2.2 High-volume Concept 2 (H2)

The second concept for high-volume factories would use the following methods for calibration.

- Plane targets for the calibration of the LiDARs
- One-point calibration for the Radars
- Object based 2D calibration for the camera recognition
- Feature-based calibration for the camera stitching

An idea concerning the potential layout of the station that incorporates all these calibration methods is illustrated in Figure 31 below.

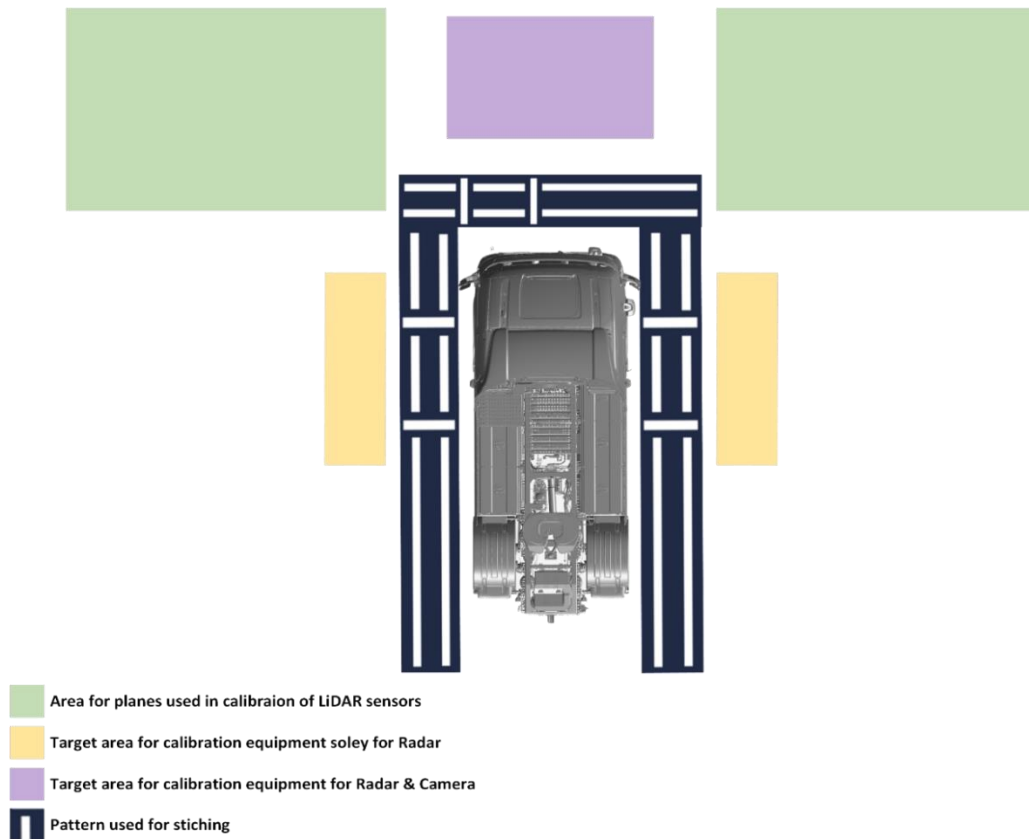


Figure 31 - Suggested layout for High-volume concept 2

For this specific concept the green area is meant to illustrate the approximate area where the three distinct planes can be located on each side. These distinct planes can for example be walls and the floor but also artificially added screens that can act as planes. These two areas could together cover the calibration needed for all LiDARs installed in the front and sides of the truck.

Area in yellow indicates the approximate area where the side-sensing Radar calibration equipment can be placed where equipment for side-sensing Radar can be placed. Similarly, to concept 1 for high-volume, the solution from the present-day station set-up can be reused.

Similar approach to the one described in concept 1 for high-volume can be implemented in this case as well in the area marked in purple. Difference would be that no need for 3D-geometrical targets to be installed as attachment on the robot would be needed since LiDAR calibration would be handed by other pieces of equipment completely. Instead, a snake-board pattern can be printed directly onto the screen.

The striped area is for the stitching of the camera sensors that can be placed in and around the truck.

For this concept to work the following requirement would have to be met:

- The trucks' position in 3D-space has to be set or measured somehow in order for calibration to be performed

- Target placement accuracy has to be guaranteed, along with ensuring high surface quality of the targets
- Stitching pattern has to be durable due to truck having to drive over it in when continuing onto the next station
- Target area in purple has to be retractable in order for the truck to be allowed continuing onto the next station

5.2.3 High-volume Concept 3 (H3)

The third concept for high-volume factories would use the following methods for calibration.

- Hole targets for the calibration of the LiDARs
- Shared-FOV method for calibration of Radars
- Object based 2D calibration for the camera recognition
- Stereo calibration for the camera stitching

An idea concerning the potential layout of the station that incorporates all these calibration methods is illustrated in Figure 32 below.

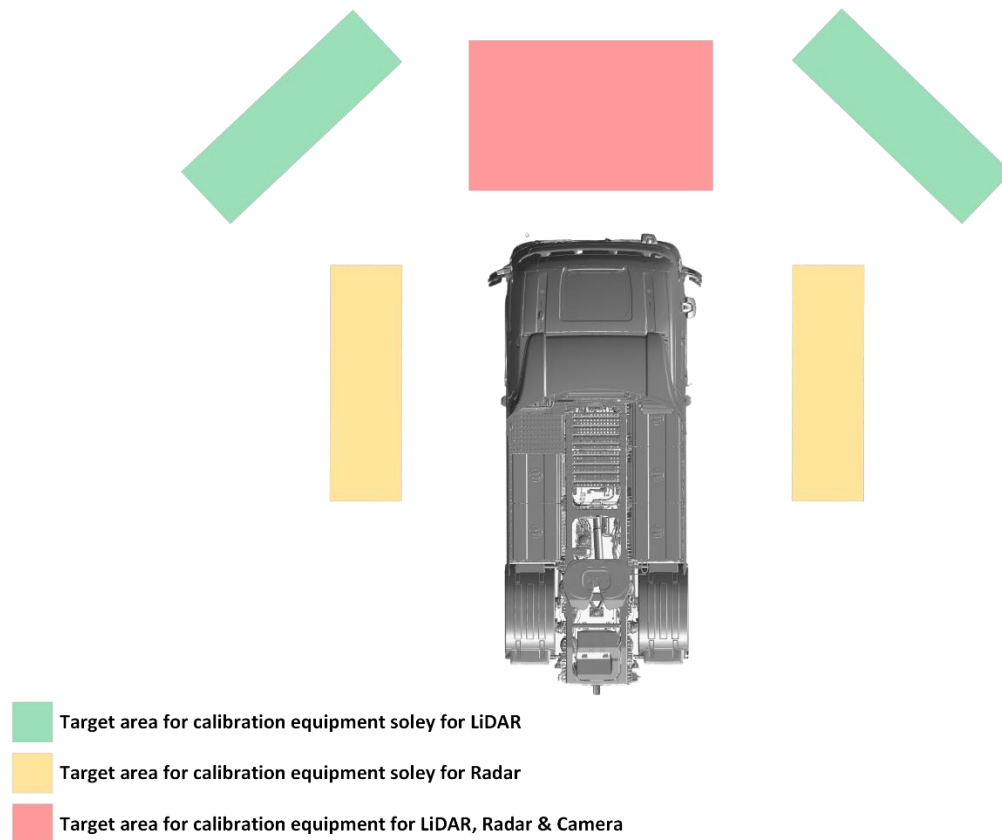


Figure 32 - Suggested layout for High-volume concept 3

This specific concept will be good at handling an increased amount of Radar sensors in for example the front of the truck, since a field of view of 45° or more will be shared for the sensors in this location. Hence, the target in the red areas will enable calibration of multiple front Radars

at the same time. The Target will also have a snake-board pattern on it for calibration of the camera. For the side-sensing Radar, the same solution as previously mentioned in concepts H1 & H2 can be used (marked in yellow), since it is impossible for these to share a field of view.

The area marked in green will be the approximate locations for the placement of the hole-targets for this specific concept. These areas will allow for calibration of LiDARs placed along the sides, front of the truck and at the corners simultaneously.

For this specific concept the camera stitch will be handled by the cameras looking at the station environment/surroundings.

For this concept to work the following requirement would have to be met:

- The trucks' position in 3D-space has to be set or measured somehow in order for calibration to be performed
- Target placement accuracy has to be guaranteed, along with ensuring high surface quality of the targets
- A shared field of view of 45° or more has to be shared across the Radars for them to be calibrated.
- In the case of static targets for LiDAR calibration all expected variations in point cloud data have to be stored and used by a system at the station
- Target area in red has to be retractable in order for the truck to be allowed continuing onto the next station

5.2.4 High-volume Concept 4 (H4)

The fourth concept for high-volume factories would use the following methods for calibration.

- Geometrical targets for the calibration of the LiDARs
- Shared-FOV method for calibration of Radars
- Dynamic calibration for the camera recognition
- Stereo calibration for the camera stitching

An idea concerning the potential layout of the station that incorporates all these calibration methods is illustrated in Figure 33 below.

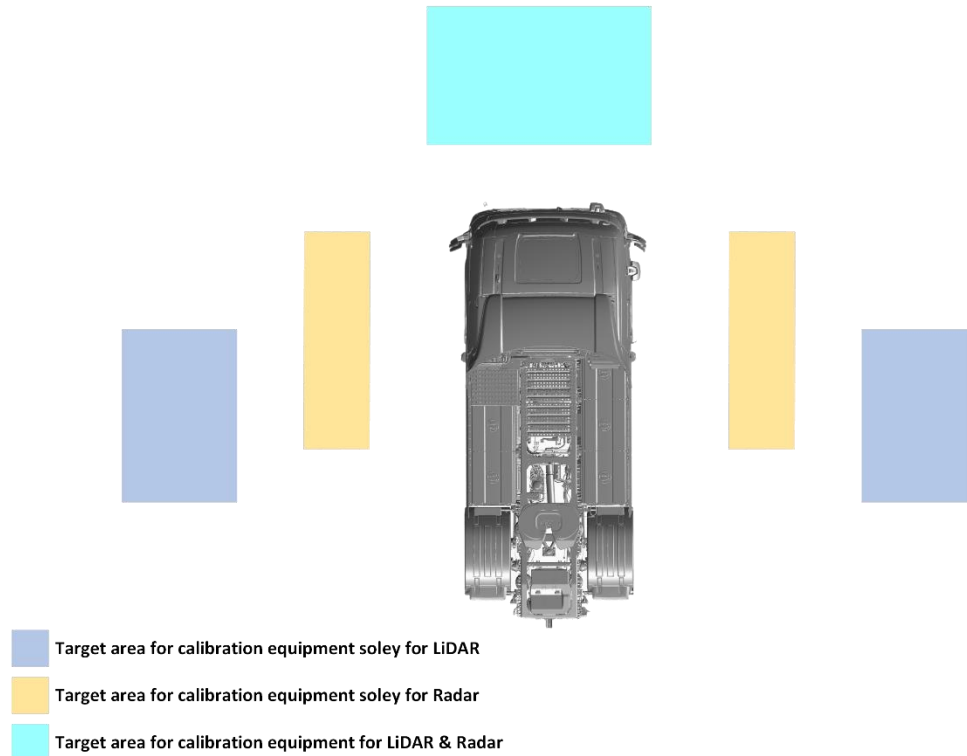


Figure 33 - Suggested layout for High-volume concept 4

This concept is very similar to concept H1 but once again allows for multiple Radars for example to be calibrated at once. However, camera recognition calibration will be handled through dynamic testing and not on the station. This will translate to a track being needed for the calibration of this to be done.

Further, Radar and LiDAR calibration will be handled in the exact same way as in concept H1. Stitching will be done similarly as in concept H3.

For this concept to work the following requirement would have to be met:

- The trucks' position in 3D-space has to be set or measured somehow in order for calibration to be performed
- Target placement accuracy has to be guaranteed, along with ensuring high surface quality of the targets
- In the case of static targets for LiDAR calibration all expected variations in point cloud data have to be stored and used by a system at the station
- A track or some sort of environment that allows for dynamic testing will be required
- Target area in turquoise has to be retractable in order for the truck to be allowed continuing onto the next station

5.2.5 High-volume Concept 5 (H5)

The fifth concept for high-volume factories would use the following methods for calibration.

- Geometrical targets for the calibration of the LiDARs

- One-point calibration for the Radars
- Object based 2D calibration for the camera recognition
- Feature-based calibration for the camera stitching

An idea concerning the potential layout of the station that incorporates all these calibration methods is illustrated in Figure 34 below.

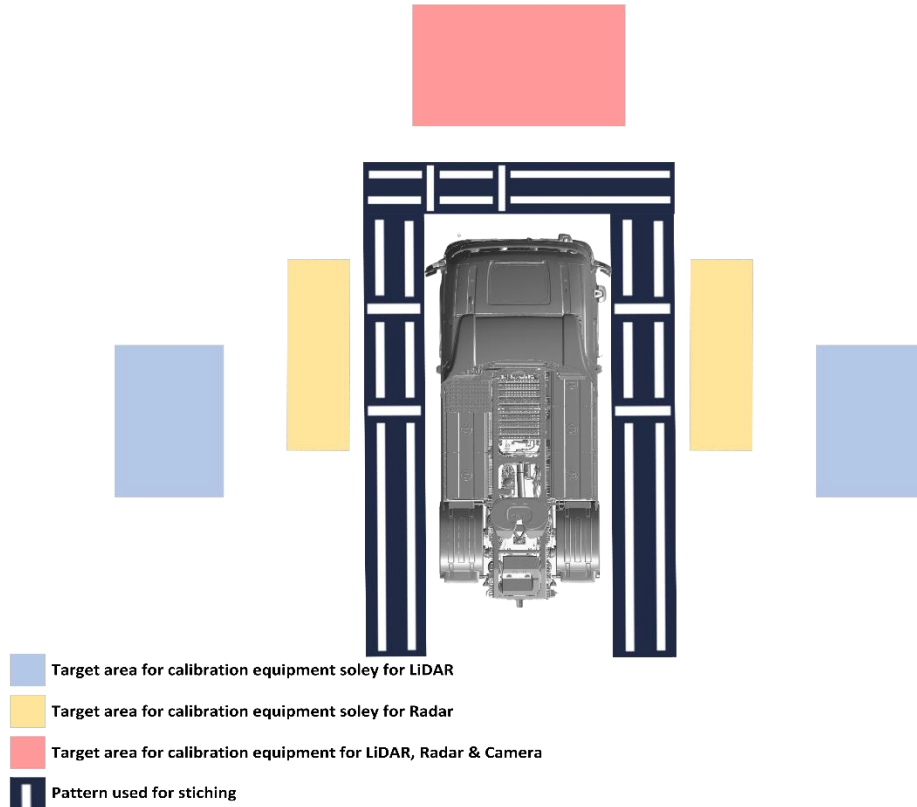


Figure 34 - Suggested layout for High-volume concept 5

This concept functions on the exact same principles as concept H1 with the only difference being how the camera recognition is calibrated. Instead of the 3D geometrical shape having snake-board patterns along its surfaces, the pattern can directly be placed on the screen used for the front Radar calibration.

For this concept to work the following requirements would have to be met:

- The trucks' position in 3D-space has to be set or measured somehow in order for calibration to be performed
- In the case of static targets for LiDAR calibration all expected variations in point cloud data have to be stored and used by a system at the station
- Target placement accuracy has to be guaranteed, along with ensuring high surface quality of the targets
- Stitching pattern has to be durable due to truck having to drive over it in when continuing onto the next station

- Target area in red has to be retractable in order for the truck to be allowed continuing onto the next station

5.2.6 Low-volume Concept 1 (L1)

The first concept for low-volume factories would use the following methods for calibration.

- Ego-motion method for LiDAR calibration.
- Dynamic calibration for Radar sensors.
- Dynamic calibration for camera sensors used for image recognition.
- The dynamic calibration method for stitching camera sensors together.

As this concept is purely based on dynamic calibration of the different perception sensors the layout of the concept is therefore a track and is illustrated in Figure 35.

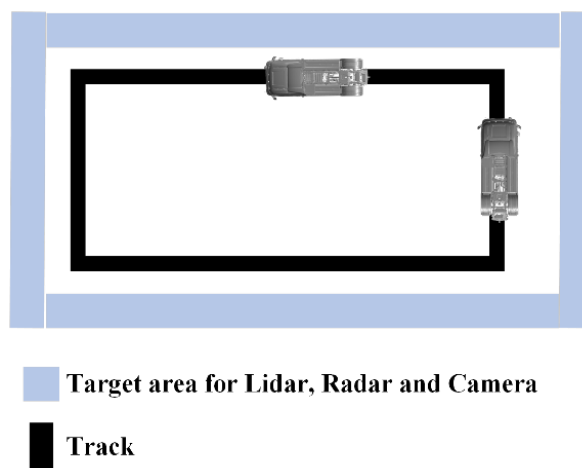


Figure 35 - Suggested layout for low-volume concept 1

Using these methods, no station will be needed as all the methods for this concept needs the truck to be driven. Instead, a designated area outside the factory where the truck can be driven on a track under specified conditions needs to be established. Using this concept for low-volume manufacturing has some positives and some negatives, The positives being that the investment for equipment is very low and the footprint in the plant itself is nonexistent. The maintenance will also be very limited as the only thing that will be needed to be maintained is the track. The negative with this concept is that if the dynamic methods don't reach the set accuracy targets it will not be viable. Meaning that reaching the set accuracy is crucial for this concept to work. The weather also needs to be favorable for the calibration methods to perform the calibration process.

For this concept to work the following requirements needs to be met.

- The dynamics methods need to meet the accuracy targets
- Designated track for testing without interference
- Favorable weather (No snow, mist or heavy rain)

5.2.7 Low-volume Concept 2 (L2)

The second concept for low-volume factories would use the following methods for calibration.

- geometrical targets method for LiDAR calibration
- One-point calibration for Radar sensors
- Object based with 2D calibration for camera recognition
- Feature-based method for camera stitching

An idea concerning the potential layout of the station that incorporates all these calibration methods is illustrated in Figure 36 below.

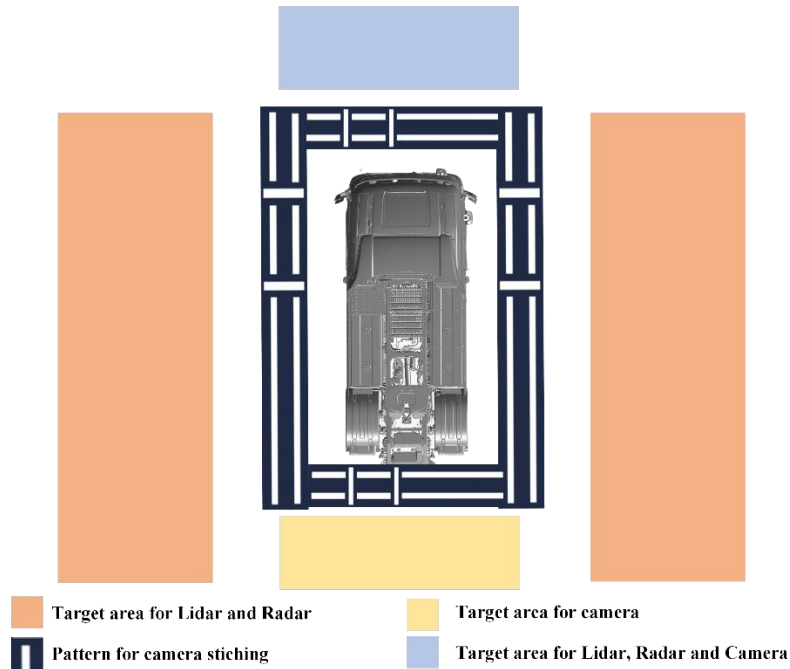


Figure 36 - Suggested layout for low-volume concept 2

This concept needs a designated calibration station to work. The station would need some geometrical targets for the LiDAR calibration and 2D planes with patterns for calibration of the camera sensors and 2D planes for calibrating the Radar sensors. One positive with this station is that it could be done with relative similar equipment as the equipment used at Tuve at the current moment. The negative with this concept is that it is relative complex and will need some precise patterns and planes to function.

For this concept to work the following requirements needs to be met.

- The LiDAR sensors needs to see geometrical targets features
- Patterns that meet the accuracy target for the calibration.
- 2D planes and geometrical targets needs to be at certain distances from the truck.
- The station needs to know where in 3D space the truck is situated.
- Targets that can move.
- The drive vector of the truck needs to be known.
- Stitching pattern has to be durable due to truck having to drive over it in when continuing onto the next station

5.2.8 Low-volume Concept 3 (L3)

The third concept for low-volume factories would use the following methods for calibration.

- Feature based method for LiDAR calibration
- Dynamic calibration for Radar sensors
- Dynamic calibration for camera sensors used for image recognition.
- The dynamic calibration method for stitching camera sensors together.

An idea concerning the potential layout of the designated spot where LiDAR sensors are calibrated using the feature-based method is illustrated in Figure 37.



Figure 37 - Suggested layout for low-volume concept 3

This concept as the first concept will need a track where the truck can be calibrated using dynamic methods. The main difference from this concept and the first one is that LiDAR sensors will be calibrated using the feature-based method instead of ego-motion method. This means that the track needs to be outfitted with a place where the truck can stop and calibrate its LiDARs. It would be favorable if this stop was surrounded by an urban like environment but not necessary for it to work. The positive with this concept that no station is needed for the calibration which means that the only manning the calibration process will need is an operator driving the truck. The negative with this station is that truck will need to stop meaning the cycle time will be longer and depending on the length of the stop more than one designated place might be needed for the LiDAR calibration.

For this concept to work the following requirements needs to be met.

- The dynamics methods need to meet the accuracy targets.
- Designated track for testing without interference.
- Favorable weather (No snow, mist or heavy rain).
- The track needs to have a place where the truck can stop and calibrate it's LiDAR sensors.

5.2.9 Low-volume Concept 4 (L4)

The fourth concept for low-volume factories would use the following methods for calibration.

- Geometrical targets method for LiDAR calibration.
- One-point calibration for Radar sensors
- Object based with 3D calibration for camera recognition
- Feature-based method for camera stitching

An idea concerning the potential layout of the station that incorporates all these calibration methods is illustrated in Figure 38 below.



Figure 38 - Suggested layout for low-volume concept 4

The fourth concept will need a station for calibrating the different sensors. This station will be outfitted with moving targets (objects) for the image recognition camera sensors. The station will also need to have 2D planes which can be used for the Radar sensor calibration. There is also a need for geometrical targets to be present at the station for LiDAR calibration. Lastly patterns on the floor or around the station needs to be present for stitching camera sensors together. The positive with this station is that if the 3D targets could be used so that the LiDAR sensors and camera sensors could be calibrated together if it is wanted. The negative with this station is that it will need a larger number of moving targets than the other concept making it more complex.

For this concept to work the following requirements needs to be met.

- Targets that can move.
- Patterns that meet the accuracy target for the calibration.
- 2D planes and geometrical targets needs to be at certain distances from the truck.

- The station needs to know where in 3D space the truck is situated.
- The drive vector of the truck needs to be known.
- Stitching pattern has to be durable due to truck having to drive over it in when continuing onto the next station

5.2.10 Low-volume Concept 5 (L5)

The fifth concept for low-volume factories would use the following methods for calibration.

- Ego-motion method for LiDAR calibration.
- One-point calibration for Radar sensors
- Object based with 2D calibration for camera recognition
- Feature-based method for camera stitching

An idea concerning the potential layout of the station that incorporates all the calibration methods, but the ego-motion method is illustrated in Figure 39.

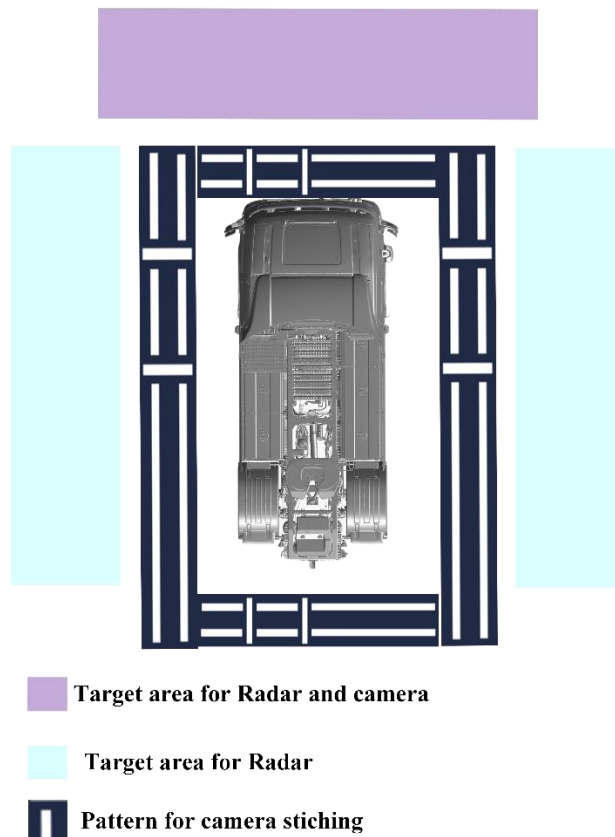


Figure 39 - Suggested layout for low-volume concept 5

The fifth concept for low-volume factories will need a designated station for calibration of Radar and camera sensors and a track where the LiDAR sensors can be calibrated. The station for this concept could be similar to the current station at Tuve with 2D planes moving in front of the sensor to calibrate them. The main differences would be the need for a track for LiDAR sensors

and patterns around the truck for stitching camera sensors. The positive for this concept is that known knowledge can be applied to the station. Another positive is that the station will not need any 3D objects for calibration. Two negatives of this concepts are that it requires both a station and a track and it will be reliant on the weather for LiDAR calibration.

For this concept to work the following requirements needs to be met.

- Targets that can move.
- Patterns that meet the accuracy target for the calibration.
- 2D planes needs to be at certain distances from the truck.
- The station needs to know where in 3D space the truck is situated.
- Designated track for testing without interference.
- Favorable weather (No snow, mist or heavy rain).
- The drive vector of the truck needs to be known.
- Stitching pattern has to be durable due to truck having to drive over it in when continuing onto the next station

5.3 Concept Screening

When all the ten concepts were created, they were filtered using an elimination matrix. Which resulted in four of the concepts being filtered out. These four concepts were H3, H4, L3 and L5 and the elimination matrix can be seen in APPENDIX A.4. This resulted in three concepts for each type of factory remaining. These three concepts of each type were then weighted against each other using the Kesselring method on a concept level instead of method-based screening. When the Kesselring method had been done one of each type of concept were left and these two were H5 and L2. The two Kesselring matrices for low and high-volume concepts can be seen in APPENDIX A.3.

5.4 Final Concepts Variations

After the concept screening the concepts H5 and L2 were the two remaining ones. Therefore, these are expanded upon further and variations are looked in to in subsequent sections.

Each concept will be benchmarked using a truck with the following specification and it can be seen in Figure 40 bellow.

- One front facing Radar
- One front facing Camera (for recognition)
- One front facing LiDAR
- Four LiDARs at the corners (one at each corner)
- Two side-sensing Radar modules (four Radars)
- Four Cameras for 360° view

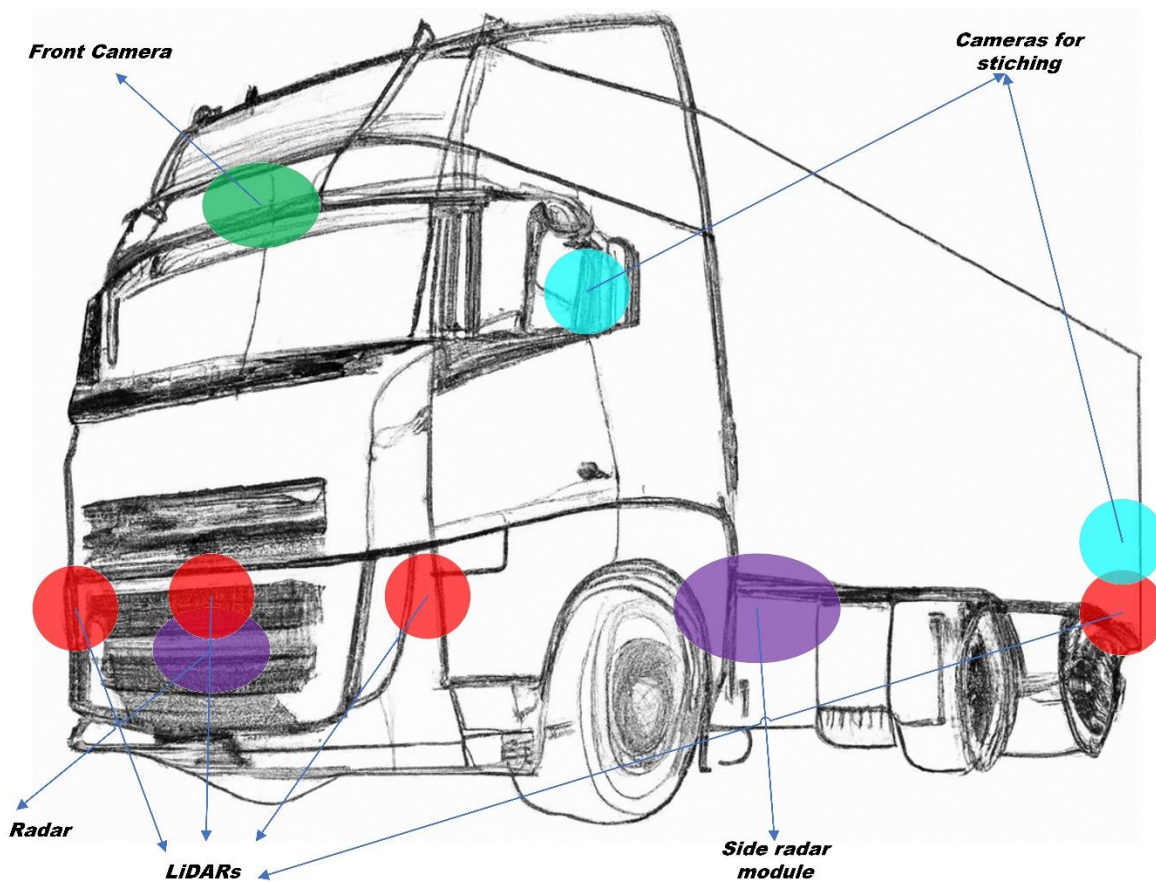


Figure 40 – Truck used for benchmarking

5.4.1 High-volume Concept H5-A (variation 1)

The following is a proposal for a calibration station concept (*Concept H5-A*) that incorporates all calibration methods included in concept H5 while at the same time aiming to reuse the existing knowledge and equipment found on the present day station, to a maximum degree. An illustration giving an overview of *Concept H5-A* can be seen in Figure 41 below.

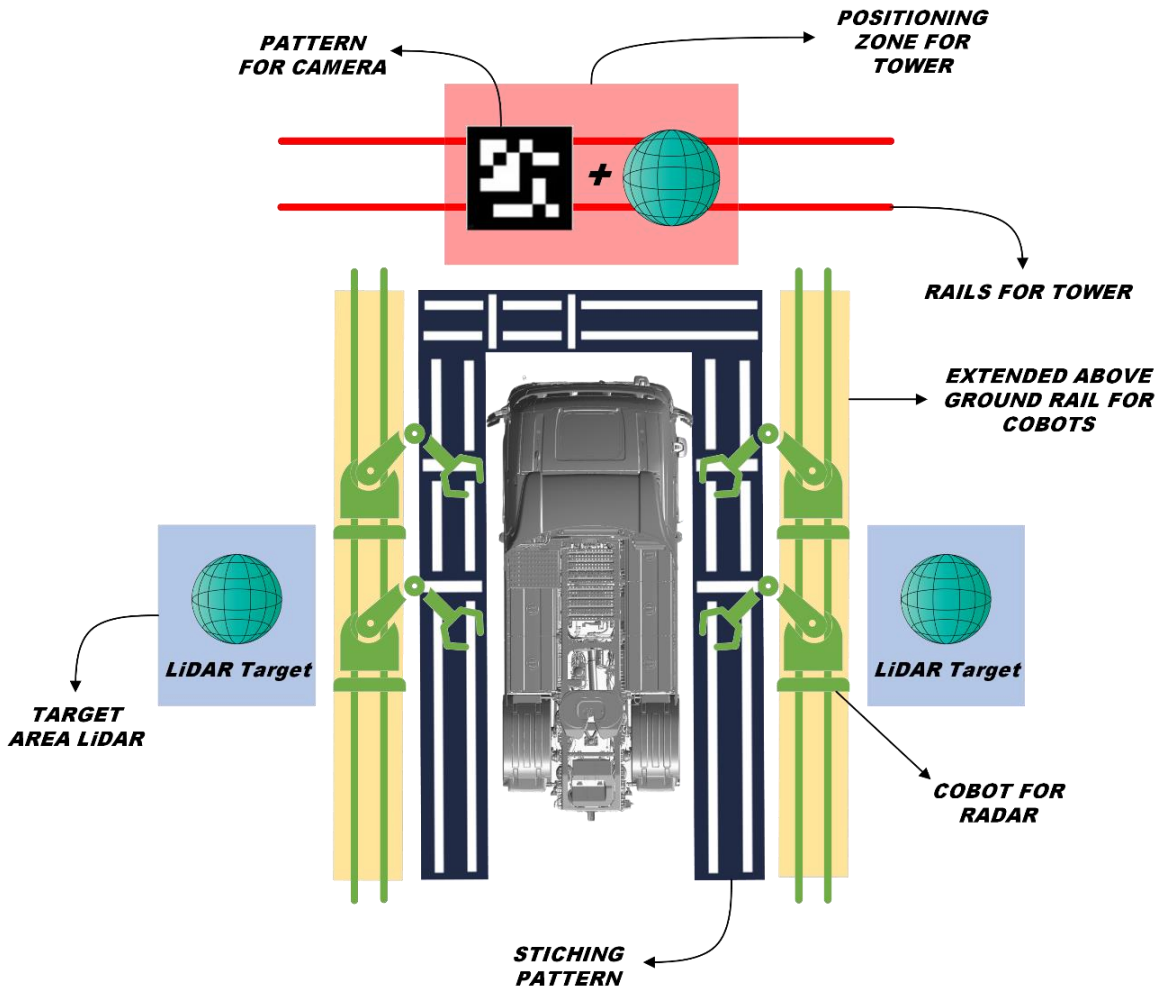


Figure 41 - Concept H5-A (above ground rails + tower)

This proposal reuses the same solutions as can be found in the present day station when it comes to the Radar and camera calibration equipment. The areas that, however, are expanded upon is when it comes to the calibration equipment for the LiDAR. This concept has designated areas where static LiDAR targets will be placed (sphere targets in illustration) at each side of the truck. These targets could either be on the floor or on walls and they would allow for full testing coverage for any LiDARs that are placed at the sides or corners of the truck, as long as they are within the field of view. Implementation of these targets would increase the footprint of the

station since bigger width compared to before is needed. The approximate increase in width could be up to **8 meters**. The length of the station could still remain **17,5 meters**.

Further, a LiDAR target is implemented at the front too, directly attached to the tower. This is needed due to the LiDAR targets at the sides not being able to cover the calibration of any LiDARs that are placed directly at the front of the truck.

The concept utilizes the same principles as the current day station when it comes the cobots used for calibration of any Radars found on the sides of the truck and the tower setup being used for the calibration of any Radars in the front. These solutions are scalable and allow for more Radars to be calibrated in the case of an increase. Reusage of these would also significantly decrease the investments needed into research and development since knowledge around them is already present.

The system of rails is also reused in this concept that the cobots and tower will move along. Specifically reusing the above ground rail system for the cobots will allow for LiDAR calibration to be done smoothly since it can be performed without the presence of any interfering objects.

Further, a stitching pattern will be present all around the truck, except for the back. This is due to it being expected that any cameras that are placed in the back of the truck will be able to be calibrated using the stitching patterns on the sides.

A rough top-level equipment list for this concept can be seen below.

Table 1 – Equipment list for concept H5-A

Equipment	Number
HMI, PLC In and Out ports	One for each equipment
Tower	One
Screens with clients for visualization	One
Cobot	Four
Target screen	Four
Control unit for cobot	Four
Rail to facilitate movement for cobots & Tower	Three
Control unit for rail	Three
Emergency break circuit	One

LiDAR target	Three
Target screen with snake board pattern	One
Equipment to calibrate the station	One
Pattern for camera stitching	One

Based on the time data gathered during the AS-IS analysis concerning the systems and equipment in combination with the overview of the equipment needed for this concept, a suggestion on the possible execution sequence is given below. Approximate times are given as well. The sequence starts with when the truck is placed correctly in the station. Another important aspect is that calibration and mechanical movements that can be done in parallel will be done so.

Table 2 - Sequence for concept H5-A

Sequence/Process	Time (seconds)
Tower forward	15
Calibration of front camera, Radar & front LiDAR	30
Target backwards & Cobots down	15
Calibration of side-Radars	15
Cobots up (safe position)	15
Calibration of corner LiDARs	30
Calibration of 360° view (stitching)	30

The total estimated sequence/process time for this concept comes down to a total of **150 seconds**. However, this only takes into consideration mechanical movement time and calibration time while at the same time, as previously mentioned, being for the scenario where parallel calibration and movement of equipment is possible. Based on the knowledge gather from the AS-IS analysis it can also be assumed that roughly 30 seconds will be added on top of this for systems to intercommunicate with each other, which would bring the total time to for the sequence/process to **180 seconds**. It should be noted that the time it takes to calculate where the truck is situated in the station would also be added to get the full sequence time.

In order for this concept to work as intended some requirements will have to be met, these are (some of these are previously discussed):

- In order for calibration to be conducted, the three-dimensional positioning of the trucks must be determined either by means of physical placement in a specific location or by the truck being stopped within a designated approximate area. Once stopped a system will have to be implemented for precise calculation of the 3D coordinates of the truck.
- Since LiDAR targets will be static in designated positions there's a need for a system which stores the variations in the expected point cloud data for each possible variation of the truck. This data will then be compared to the real time data gathered by the LiDARs at the calibration station in order for the discrepancies to be measured.
- No operators or interfering objects can be on the station premises while calibration procedures are ongoing since this will lead to discrepancies in data gathered by sensors. Exception for this would be if an operator sits in the truck while calibration is performed.
- No operators or interfering objects can be on the station premises while mechanical movements are being performed for safety and collision preventive measures.
- Accuracy of target placement has to be guaranteed, along with ensuring high surface quality of all the targets.
- Stitching pattern has to be durable due to truck having to drive over it in when continuing onto the next station.
- Drive-vector has to be known or measured.
- A certain space between the targets and sensors has to be guaranteed in order for proper calibration to be executed.

Some of these requirements are crucial in order for calibration to even be performed, such as the first requirement which is why it will be discussed and theorized how it can be solved in the discussion section.

Overall, this concept can be seen as an upgrade to the current one where LiDAR targets are added, which can be beneficial from a point of view on investment. The total time at the station for this specific concept is roughly estimated to be around 180 seconds but relies on working parallel movement of equipment and parallel calibration. This is an acceptable time. Theoretically only one operator which drives the truck into the designated area is needed for this concept.

5.4.2 High-volume Concept H5-B (variation 2)

Concept H5-B is a proposal that is very similar to concept H5-A with the difference being that the rails for the cobots are placed on the ground instead. This concept also aims at reusing the knowledge and equipment from the current station to a maximum degree. The overview for this concept can be seen in Figure 42.

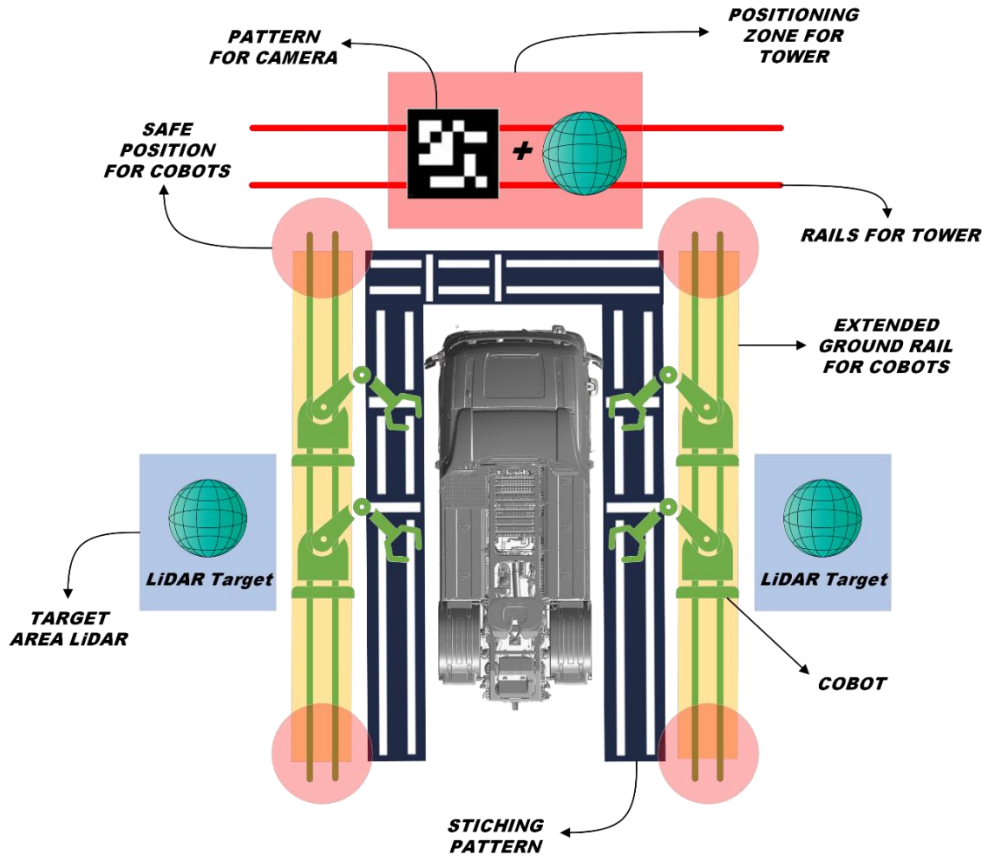


Figure 42 - Concept H5-B (ground rails + tower)

Most of the functions for this concept are already described in the sub-section about concept H5-A. However, having in mind the rails for the cobots will be on the ground there's a need for dedicated safe positions for the cobots at the end of the rails. Reasoning for this is to avoid any blockage of the LiDARs field of view towards the targets. By placing the cobots at the end of the rails this is prevented due to it allowing for a clear view of all the LiDAR targets. This will have an impact on the station sequence.

The footprint for this specific concept is calculated to be approximately the same as for concept H5-A, hence, 8 meters wide and 17,5 meters long. This proposal also required only one operator at the station that will be responsible for driving the truck correctly into it and driving the truck into the next station the calibration sequence.

A rough top-level equipment list for this concept can be seen below.

Table 3 - Equipment List for concept H5-B

Equipment	Number
HMI, PLC In and Out ports	One for each equipment

Tower	One
Screens with clients for visualization	One
Cobot	Four
Target screen	Four
Control unit for cobot	Four
Rail to facilitate movement for cobots & tower	Three
Control unit for rail	Three
Emergency break circuit	One
LiDAR target	Three
Target screen with snake board pattern	One
Equipment to calibrate the station	One
Pattern for camera stitching	One

A suggestion for the possible execution sequence for this proposal can be seen below.

Table 4 - Sequence for concept H5-B

Sequence/Process	Time (seconds)
Tower forward	15
Calibration of front camera, Radar & front LiDAR	30
Tower backwards & Cobots move into calibration position	25
Calibration of side-Radars	15
Cobots move back into safe corner positions	25
Calibration of corner LiDARs	30

The total estimated sequence/process time for this concept comes down to a total of **170 seconds**. The difference compared to previously discussed concepts is that the cobots would have to travel a longer distance both when moving into calibration position but also when going back into the safety positions. This impacts the overall time, hence the increase of 20 seconds compared to concepts H5-A. Adding the rough estimate when it comes to system communication time leads to a total station time of **200 seconds**. It should be noted that the time it takes to calculate where the truck is situated in the station would also be added to get the full sequence time.

The maintenance aspect for this proposal would be easier since the equipment would be placed on ground level instead of on rails above ground, allowing for easier reachability.

In order for this concept to work as intended some requirements will have to be met, these are (some of these are previously discussed):

- In order for calibration to be conducted, the three-dimensional positioning of the trucks must be determined either by means of physical placement in a specific location or by the truck being stopped within a designated approximate area. Once stopped a system will have to be implemented for precise calculation of the 3D coordinates of the truck.
- Since LiDAR targets will be static in designated positions there's a need for a system which stores the variations in the expected point cloud data for each possible variation of the truck. This data will then be compared to the real time data gathered by the LiDARs at the calibration station in order for the discrepancies to be measured.
- No operators or interfering objects can be on the station premises while calibration procedures are ongoing since this will lead to discrepancies in data gathered by sensors. Exception for this would be if an operator sits in the truck while calibration is performed.
- No operators or interfering objects can be on the station premises while mechanical movements are being performed for safety and collision preventive measures.
- Accuracy of target placement has to be guaranteed, along with ensuring high surface quality of all the targets.
- Stitching pattern has to be durable due to truck having to drive over it in when continuing onto the next station.
- Drive-vector has to be known or measured.
- A certain space between the targets and sensors has to be guaranteed in order for proper calibration to be executed.

Overall, this proposal can also be seen as an upgrade to the current station with LiDAR targets being added. However, it would require development of a new rail system on the ground level which the cobots can operate on, which could increase the investment needed. The total estimated time for this concept is around 200 seconds, which is acceptable, but it relies on parallel movement of equipment and calibration being available. Additionally, this concept only

Since there is an absence of a tower in this proposal, the calibration of the front camera and Radar will be handled by a cobot as well. This cobot is marked in red in the figure above. The target/screen mounted on it has a snake-board pattern printed on it in order to be able to handle both calibration of Radar and camera sensors. This cobot will be tasked with handling a multitude of tasks including; partly calibration of the side-sensing Radar, calibration of Radar in the front of the truck, calibration of front-facing camera. The remaining Radars will be calibrated using the cobots marked in green.

Similarly to previously mentioned concepts, the calibration of the 360° view will be performed by the usage of the stitching pattern around the truck.

A rough top-level equipment list for this concept can be seen below.

Table 5 - Equipment List for concept H5-C

Equipment	Number
HMI, PLC In and Out ports	One for each equipment
Screens with clients for visualization	One
Cobot	Five
Target screen with snake board pattern	One
Target screen	Three
LiDAR target	Three
Control unit for cobot	Five
Rail to facilitate movement for cobots	Two
Control unit for rail	Two
Emergency break circuit	One
Equipment to calibrate the station	One
Control unit for rail	Two
Pattern for camera stitching	One

A suggestion for the possible execution sequence for this proposal can be seen below. Similarly to the previously mentioned concepts, this sequence is based on the allowance of parallel movement of equipment and calibration.

Table 6 - Sequence for concept H5-C

Sequence/Process	Time (seconds)
LiDAR target & side-sensing Radars target move down	15
Calibration of side-sensing Radar & front LiDAR	30
LiDAR target + side-sensing targets move up & red cobot move to the front	20
Calibration of front camera and front Radar	20
Red cobot move up	10
Calibration of corner LiDARs	30
Calibration of 360° view (stitching)	30

The total estimated sequence/process time for this concept comes down to a total of **155 seconds** not including the system communication time. System communication time is calculated to be approximately 30 seconds which increases the total station time to **185 seconds**. It should be noted that the time it takes to calculate where the truck is situated in the station would also be added to get the full sequence time.

In order for this concept to work as intended some requirements will have to be met, these are (some of these are previously discussed):

- In order for calibration to be conducted, the three-dimensional positioning of the trucks must be determined either by means of physical placement in a specific location or by the truck being stopped within a designated approximate area. Once stopped a system will have to be implemented for precise calculation of the 3D coordinates of the truck.
- Since LiDAR targets will be static in designated positions there's a need for a system which stores the variations in the expected point cloud data for each possible variation of the truck. This data will then be compared to the real time data gathered by the LiDARs at the calibration station in order for the discrepancies to be measured.
- No operators or interfering objects can be on the station premises while calibration procedures are ongoing since this will lead to discrepancies in data gathered by sensors. Exception for this would be if an operator sits in the truck while calibration is performed.

- No operators or interfering objects can be on the station premises while mechanical movements are being performed for safety and collision preventive measures.
- Accuracy of target placement has to be guaranteed, along with ensuring high surface quality of all the targets.
- Stitching pattern has to be durable due to truck having to drive over it in when continuing onto the next station.
- Drive-vector has to be known or measured.
- A certain space between the targets and sensors has to be guaranteed in order for proper calibration to be executed.
- A collision preventive algorithm would have to be implemented for the cobots or an algorithm that enables the cobots to know their position in relation to each other.
- Bigger cobots with extended reachability will be required in order for the sensors in the front to be calibrated correctly.

In essence, this proposal introduces a highly scalable solution that facilitates easy handling and calibration of a greater number of sensors that are to be installed on the truck. The approximate time that a truck would spend on the station is 185 seconds for the truck used for benchmarking. However, for calibration sequence to be executed properly more preventive measures or algorithms would most likely have to be implemented. Furthermore, this concept would only require one operator to be present at the station.

5.4.4 Final Low-volume Concept L2

As stated previously this concept for low-volume factories would use the following calibration methods

- Geometrical target method for LiDAR calibration
- One-point calibration for Radar sensors
- Object based with 2D calibration for camera recognition
- Feature-based method for camera stitching

Using these calibration methods would require a designated station for them to be performed. An illustration on how the layout of the station in more detail can be seen in Figure 44 below

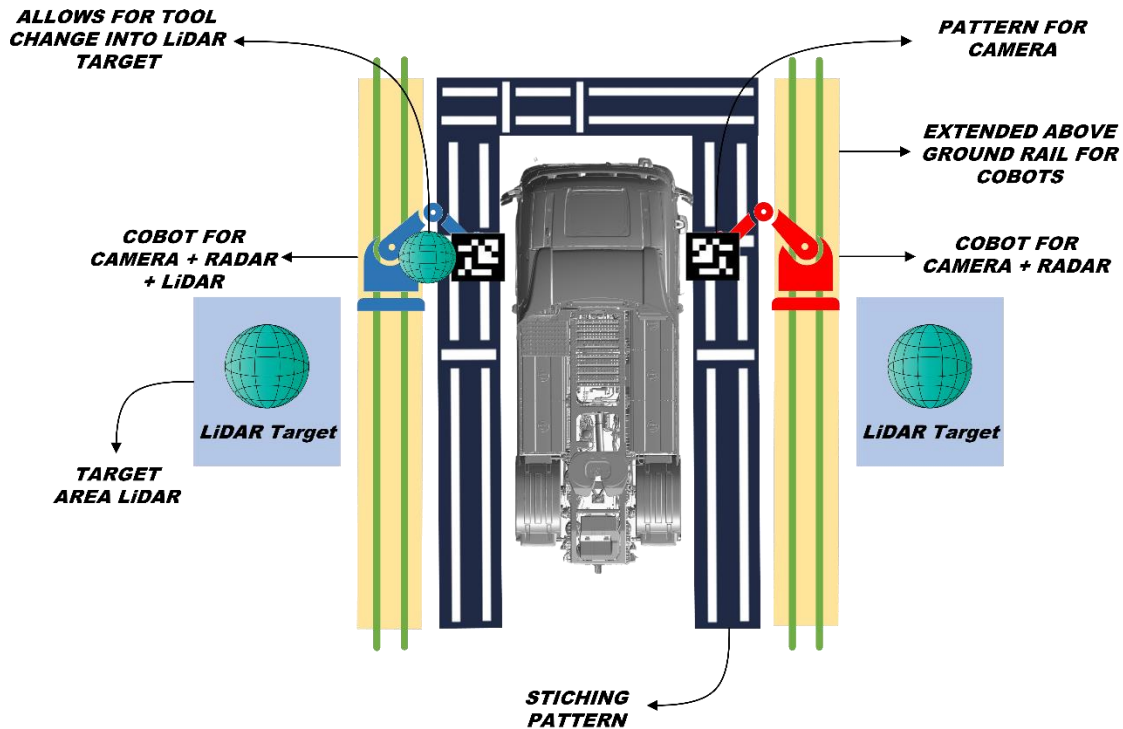


Figure 44 – Detailed layout of the final low-volume concept

The station would need the measurements 15 meters in length and 8 meters in width. The height of the station would need to be higher than the truck which means 5 meters in height would suffice. The reasoning behind the width of 8 meters can be read in 5.4.1.

Why it is recommended to use cobots in a low-volume factory instead of using operators holding the target screens is because that solution for placement of targets wouldn't be robust. That solution would also not be able to ensure that the accuracy target is met each cycle as each operator might do the procedure differently. Instead of recommending Volvo to find new solutions on how the placement of the rail for the cobots should be done it is instead recommended to use the existing one. This is recommended as it is already used and no extra resources would be needed to be invested in the production of a new way of placing the rail in the station. The difference from the existing rail solution and the one being recommended here is that it needs to be able to have larger cobots connected to it and be longer as the cobots need to be able to reach the front and back of the truck.

The pattern for camera stitching seen in the figure will be used for the feature-based method for camera stitching. These patterns will be present as seen in the figure above, on both sides of the truck and in the front.

The cobot marked in red in the figure above will be equipped with a target screen which can be used to calibrate both camera and Radar sensors. The target screen would therefore need to have a snake board pattern on it and be of a material which can be used for Radar calibration. The cobot will be able to calibrate Radar and camera sensors situated in the front, back and the right side of the truck.

The cobot marked in blue in the figure above will be equipped with both a target screen for Radar and camera sensors. The target screen would be the same as the one mentioned prior. However, it will also be able to change the target screen with a geometrical target for LiDAR sensors. This would make the cobot equip to calibrate Radar and camera sensors in front, back and the left side of the truck but also able to calibrate LiDAR sensors in the front and the back of the truck.

It is important to remember that the station itself also needs to be calibrated. This can be done by using a dummy truck which can be used to calibrate the station.

A rough top-level equipment list for the concept to function will be presented below. The current state analysis is used as a standard for what is needed for a station.

Table 7 - Equipment List for concept L2

Equipment	Number
HMI, PLC In and Out ports	One for each equipment
Screens with clients for visualization	One
Cobot	Two
Target screen with snake board pattern	Two
LiDAR target	Three
Equipment for Target change	One
Control unit for cobot	Two
Rail to facilitate movement for cobots	Two
Control unit for rail	Two
Emergency break circuit	One
Equipment to calibrate the station	One
Pattern for camera stitching	One

Based on the time data gathered during the current state analysis concerning the systems and equipment in combination with the overview of the equipment needed for this concept, a suggestion on station sequence will be giving below. Sequence starts when truck is placed correctly in the station. Another important aspect is that calibration and mechanical movements that can be done in parallel will be done so.

Table 8 - Sequence for concept L2

Sequence/Process	Time (seconds)
Blue cobot move in position for LiDAR calibration	15
Calibration of front LiDAR	30
Blue& red cobot move to the front	20
Blue cobot change target to screen target	60
Calibration of front camera and front Radar	20
Both cobots move up and to new position (side sensing front)	30
Red cobot move up	10
Calibration of side sensing front	10
Move cobots to side sensing Radar back	20
Calibration of side sensing back	10
Move cobots to home position	20
Calibration of corner LiDARs	30
Calibration of 360° view (stitching)	30
Blue cobot change back to LiDAR target	60
Calibration of 360° view (stitching)	30

The total estimated sequence/process time for this concept comes down to a total of **355 seconds** not including the system communication time. System communication time is calculated to be approximately 45 seconds which increases the total station time to **400 seconds**. It should be noted that the time it takes to calculate where the truck is situated in the station would also be added to get the full sequence time.

This concept will have several requirements which will need to be met and bellow they will be stated.

- In order for calibration to be conducted, the three-dimensional positioning of the trucks must be determined either by means of physical placement in a specific location or by the truck being stopped within a designated approximate area. Once stopped a system will have to be implemented for precise calculation of the 3D coordinates of the truck.
- Since LiDAR targets will be static in designated positions there's a need for a system which stores the variations in the expected point cloud data for each possible variation of the truck. This data will then be compared to the real time data gathered by the LiDARs at the calibration station in order for the discrepancies to be measured.
- No operators or interfering objects can be on the station premises while calibration procedures are ongoing since this will lead to discrepancies in data gathered by sensors. Exception for this would be if an operator sits in the truck while calibration is performed.
- No operators or interfering objects can be on the station premises while mechanical movements are being performed for safety and collision preventive measures.
- Accuracy of target placement has to be guaranteed, along with ensuring high surface quality of all the targets.
- Stitching pattern has to be durable due to truck having to drive over it in when continuing onto the next station.
- Drive-vector must be known or measured.
- A certain space between the targets and sensors has to be guaranteed in order for proper calibration to be executed.
- A collision preventive algorithm would have to be implemented for the cobots or an algorithm that enables the cobots to know their position in relation to each other.
- Bigger cobots with extended reachability will be required in order for the sensors in the front to be calibrated correctly.

Suggestions on how to meet these requirements will be discussed in the next chapter.

In conclusion, this proposal introduces a highly scalable solution that facilitates easy handling and calibration of a greater number of sensors that are to be installed on the truck. The approximate time that a truck would spend on the station is 400 seconds for the truck used for benchmarking. However, this solution would not suffice in a high-volume factory where time is of the essence. For a low-volume factory this solution can easily be implemented and as it uses the same calibration methods as the high-volume concept knowledge and equipment can be exchanged between the factories.

6 Discussion

During the AS-IS analysis the calibration methods employed at the current station were investigated and were deemed to be robust. These methods proved their reliability and effectiveness in a factory setting as they ensured an accurate calibration of the perception sensor on the truck. This was one of the main reasons for reusing them in the final concepts instead of adopting a more speculative and exploratory approach. However, the thesis does present some concepts where more speculative methods were used, that could potentially be areas of further investigation. Another aspect that was discovered was that pieces of equipment found on the current calibration station were identified to allow a high degree of scalability. For example, the rail system could be outfitted with more cobots without causing any disturbances in the process. The rail system also allows the cobots to move alongside the truck ensuring precise positioning. Generally, reusing this system and knowledge surrounding it would decrease the need for investment into research and development for new pieces of equipment. This is highly favorable from an investment standpoint. Further, upgrading the cobots to allow for higher reachability and multifunctional use would be very favorable as it could eliminate the need for a tower in front of the truck. Making the targets the cobots hold multifunctional would allow for multiple sensor types to be calibrated using the same cobots, hence, minimizing investment.

As the literature study revealed integration of LiDAR and camera stitching will be necessary in attaining higher levels of autonomy for the truck. Consequently, integration of these will require the necessary targets to facilitate the calibration of these types of sensors. Potential target areas are showcased in the concept section of the report. However, for these to work new systems will need to be developed. For example these systems will handle all expected variations of the point-cloud data for all possible variations of the truck.

Implementing all the above changes would, however, automate most of the process the need for three operators as seen in the current station would decrease to one operator. Instead there would have to be a requirement on no operators being present in the station while the calibration process is ongoing since this would create discrepancies in the data sets.

Now the discussion will shift towards how to solve some of the requirements for the final concepts. There are some overlapping requirements in the concepts such as the truck's position in 3D space needing to be known. This requirement can be solved in a myriad of different ways but three of the solutions will be discussed here but these solutions are only suggestions and would need further investigation. The first solution for the requirement is scanning the tires of the truck to calculate the position of the truck. The scanning process can either be done by a 3D camera scanning the tire or a laser sensor which is moved over the tire to scan it. The 3D camera would therefore be stationary, and the laser would be held by a cobot so it can scan over the tire this can be seen in Figure 45 below.

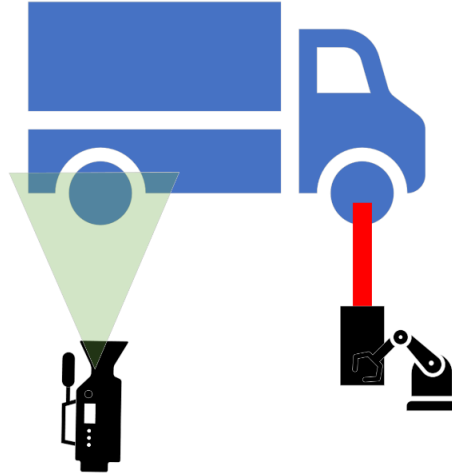


Figure 45 - Suggested ways scan the tires of the truck

Another way to determine the trucks position is too in some way place the truck in a known position after it has been driven into the station by an operator. This can be done in different ways, however, the way discussed here is to drive the truck onto frictionless wheels and use mechanical pushers that force the truck into the known position. Figure 46 demonstrates this idea. This particular idea would eliminate the need for a whole system to calculate where in 3D-space the truck is situated, which might reduce the system communication time. The weakness with this solution is that the investment needed for this is massive and if anything breaks the maintenance required would take a long time and create a bottleneck in the production flow. For example, if a laser sensor breaks from the previous solution, it could easily be replaced. This would take nearly no time in comparison too if any of the mechanical parts needed for pushing the truck into position would breakdown.



Figure 46 - Illustration of idea using mechanical pushers

The last solution to determine the position of the truck is to place a 3D camera in the ceiling of the station. Then with the help of the 3D camera calculate exactly how the truck is situated inside the station. Aids to doing this procedure could either have a reference point on the truck itself or calculate the position of the truck in relation for example the stitching pattern. This idea is illustrated in Figure 47.

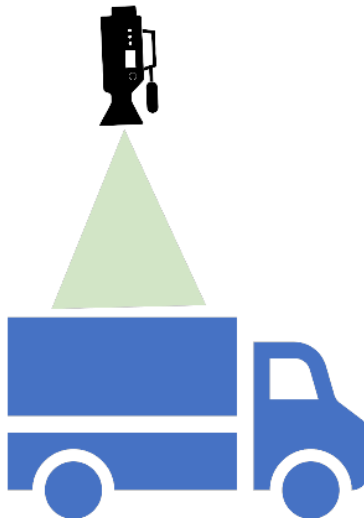


Figure 47 - Image recognition solution

Another requirement which needs to be discussed is that the drive-vector of the truck needs to be known. However, if assumed that the wheel alignment procedure is done before the truck reaches the new calibration station it is assumed that the drive vector is stored in some system.

As touched upon in the concept requirements a database which stores all expected point cloud values for all possible variations of the truck will have to be implemented for LiDAR calibration. This is a challenge as it will include huge amounts of data however, it should be noted that something similar is already present for Radar sensors. This allows knowledge to be reused in this specific area.

It is important to mention that even though all the different variants of the high-volume concept have the capacity to calibrate all trucks with only one station. It would be preferable to invest in two stations to eliminate creating a massive bottleneck in the process when maintenance is needed to be done in the station. Having two calibration stations would also lessen the burden on the station when shortages of material and similar events occur.

7 Conclusion

In conclusion the suggested concepts for both high and low-volume factories would utilize the same calibration methods. This is as these four calibration methods ranked the highest and allows for high scalability and interoperability. The difference between them is instead in the set-up of the station and the investment needed to implement them. Where a low-volume factory is not as dependent on the time the calibration process takes it is not as necessary to have more than two cobots. The calibration of the different sensors can also be done in sequence instead of being done in parallel. In the high-volume case where time is of much greater importance more cobots are used to save time on mechanical movements and where it is possible calibration of different sensors are done in parallel. This however, results in the high-volume concepts needing a larger investment and are of a higher complexity than the low-volume concept. The requirements on the concepts also share a lot of commonalities as they use the same calibration methods which means knowledge and resources can be shared between the different types of factories.

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A Appendix

A.1 Morphological Matrices for High- & Low-volume

HIGH VOLUME FACTORY

Function	Option 1	Option 2	Option 3
Calibrate lidar	Geometrical targets	Plane targets	Hole targets
Calibrate radar	One-point	Shared FOV	
Calibrate camera recognition	Object based 3D	Object based 2D	Dynamic
Calibrate camera stitching	Feature-based	Stereo	

- Concept 1: 1 – 1 – 1 – 1
- Concept 2: 2 – 1 – 2 – 1
- Concept 3: 3 – 2 – 2 – 2
- Concept 4: 1 – 2 – 3 – 2
- Concept 5: 1 – 1 – 2 – 1

LOW VOLUME FACTORY

Function	Option 1	Option 2	Option 3
Calibrate lidar	Ego-motion	Feature-based	Geometrical targets
Calibrate radar	One-point	Dynamic	
Calibrate camera recognition	Object based 3D	Object based 2D	Dynamic
Calibrate camera stitching	Feature-based	Dynamic	

- Concept 1: 1 – 2 – 3 – 2
- Concept 2: 3 – 1 – 2 – 1
- Concept 3: 2 – 2 – 3 – 2
- Concept 4: 3 – 1 – 1 – 1
- Concept 5: 1 – 1 – 2 – 1

A.2 Kesseling Matrices for Calibration Methods

Radar low volyme												
Criteroon	Weight	Ideal		One-point		Absorb chamber		Dynamic		Shared FOV		
		v	t	v	t	v	t	v	t	v	t	
Maximize Target tolerance	3	5	15	5	15	5	15	5	15	3	9	
Maximize Accuracy / performance	5	5	25	4	20	5	25	3	15	4	20	
Minimize Process time	1	5	5	4	4	2	2	1	5	5	5	
Minimize Investment	5	5	25	3	15	1	5	5	25	2	10	
Minimize Footprint	4	5	20	5	20	1	4	5	20	4	16	
Minimize Manning	2	5	10	5	10	5	10	3	6	5	10	
Minimize Maintenance	3	5	15	3	9	3	9	5	15	4	12	
Minimize Complexity	5	5	25	3	15	1	5	5	25	3	15	
Maximize Robustness	4	5	20	4	16	4	16	2	8	3	12	
Maximize scalability	4	5	20	4	16	2	8	1	4	4	16	
Maximize interoperability	4	5	20	3	12	2	8	1	4	3	12	
Total		200		152		107		142		137		
Fulfilment		1		0,76		0,54		0,71		0,69		
Ranking				1		4		3		2		

Radar High volyme												
Criteroon	Weight	Ideal		One-point		Absorb chamber		Dynamic		Shared FOV		
		v	t	v	t	v	t	v	t	v	t	
Maximize Target tolerance	3	5	15	5	15	5	15	5	15	3	9	
Maximize Accuracy / performance	5	5	25	4	20	5	25	3	15	4	20	
Minimize Process time	5	5	25	4	20	2	10	1	5	5	25	
Minimize Investment	3	5	15	3	9	1	3	5	15	2	6	
Minimize Footprint	3	5	15	5	15	1	3	4	12	4	12	
Minimize Manning	2	5	10	5	10	5	10	3	6	5	10	
Minimize Maintenance	4	5	20	3	12	3	12	5	16	4	16	
Minimize Complexity	2	5	10	3	6	1	2	5	10	3	6	
Maximize Robustness	5	5	25	4	20	4	20	2	10	3	15	
Maximize scalability	5	5	25	4	20	2	10	1	5	4	20	
Maximize interoperability	5	5	25	5	25	2	10	1	5	3	15	
Total		210		172		120		114		154		
Fulfilment		1		0,82		0,57		0,54		0,73		
Ranking				1		3		4		2		

Lidar High volyme															
Criteroon	Weight	Ideal		Geometrical targets		plane target		Hole targets		Ego-motion		Information based		Feature based	
		v	t	v	t	v	t	v	t	v	t	v	t	v	t
Maximize Target tolerance	3	5	15	2	6	4	12	3	9	5	15	5	15	5	15
Maximize Accuracy / performance	5	5	25	4	20	5	25	4	20	3	15	3	15	3	15
Minimize Process time	5	5	25	4	20	3	15	4	20	1	5	2	10	2	10
Minimize Investment	3	5	15	3	9	3	9	3	9	5	15	5	15	5	15
Minimize Footprint	3	5	15	4	12	3	9	3	9	5	15	3	9	5	15
Minimize Manning	2	5	10	3	6	3	6	3	6	4	8	4	8	4	8
Minimize Maintenance	4	5	20	4	16	4	16	4	16	5	20	4	16	4	16
Minimize Complexity	2	5	10	2	4	3	6	3	6	5	10	4	8	5	10
Maximize Robustness	5	5	25	4	20	4	20	4	20	2	10	4	20	2	10
Maximize scalability	5	5	25	5	25	3	15	3	15	2	10	3	15	3	15
Maximize interoperability	5	5	25	5	25	5	25	5	25	3	15	3	15	2	10
Total		210		163		158		155		138		146		139	
Fulfilment		1.0		0,78		0,75		0,74		0,66		0,70		0,66	
Ranking				1		2		3		6		4		5	

Lidar Low volyme																
Criteroon	Weight	Ideal			Geometrical targets		plane target		Hole targets		Ego-motion		Information based		Feature based	
		v	t		v	t	v	t	v	t	v	t	v	t	v	t
Maximize Target tolerance	3	5	15	2	6	4	12	3	9	5	15	5	15	5	15	
Maximize Accuracy / perform	5	5	25	4	20	5	25	4	20	3	15	3	15	3	15	
Minimize Process time	1	5	5	4	4	3	3	4	4	1	1	2	2	2	2	
Minimize Investment	5	5	25	3	15	3	15	3	15	5	25	5	25	5	25	
Minimize Footprint	4	5	20	4	16	3	12	3	12	5	20	3	12	5	20	
Minimize Manning	2	5	10	3	6	3	6	3	6	4	8	4	8	4	8	
Minimize Maintenance	3	5	15	4	12	4	12	4	12	5	15	4	12	4	12	
Minimize Complexity	5	5	25	4	20	3	15	3	15	5	25	4	20	5	25	
Maximize Robustness	4	5	20	4	16	4	16	4	16	2	8	4	16	2	8	
Maximize scalability	4	5	20	5	20	3	12	3	12	2	8	3	12	3	12	
Maximize interoperability	4	5	20	5	20	5	20	5	20	3	12	3	12	2	8	
							0									
Total			200		155		148		141		152		149		150	
Fulfilment			1		0,78		0,74		0,71		0,76		0,75		0,75	
Ranking					4		3		5		6		2		1	

Camera recognition high volyme																
Criteroon	Weight	Ideal			Object based 3D		Object based 2D		Self calibration		Video training		Deep learning algorithm		Dynamic	
		v	t		v	t	v	t	v	t	v	t	v	t	v	t
Maximize Target tolerance	3	5	15	1	3	3	9	5	15	2	6	4	12	4	12	
Maximize Accuracy / performance	5	5	25	4	20	5	25	3	15	2	10	1	5	2	10	
Minimize Process time	5	5	25	3	15	4	20	2	10	2	10	2	10	2	10	
Minimize Investment	3	5	15	3	9	4	12	2	6	4	12	3	9	5	15	
Minimize Footprint	3	5	15	3	9	4	12	5	15	3	9	4	12	4	12	
Minimize Manning	2	5	10	3	6	4	8	5	10	3	6	3	6	3	6	
Minimize Maintenance	4	5	20	3	12	4	16	3	12	3	12	3	12	5	20	
Minimize Complexity	2	5	10	3	6	4	8	1	2	2	4	1	2	4	8	
Maximize Robustness	5	5	25	5	25	5	25	1	5	2	10	1	5	2	10	
Maximize scalability	5	5	25	4	20	5	25	1	5	1	5	2	10	2	10	
Maximize interoperability	5	5	25	4	20	5	25	1	5	1	5	3	15	2	5	
Total			210		145		185		100		89		98		118	
Fulfilment			1		0,69		0,88		0,48		0,42		0,47		0,56	
Ranking					3		1		6		8		7		5	

camera recognition low volyme																
Criteroon	Weight	Ideal			Object based 3D		Object based 2D		Self calibration		Video training		Deep learning algorithm		Dynamic	
		v	t		v	t	v	t	v	t	v	t	v	t	v	t
Maximize Target tolerance	3	5	15	1	3	3	9	5	15	2	6	4	12	4	12	
Maximize Accuracy / performa	5	5	25	4	20	5	25	3	15	2	10	1	5	2	10	
Minimize Process time	1	5	5	3	3	4	4	2	2	2	2	2	2	2	2	
Minimize Investment	5	5	25	3	15	4	20	2	10	4	20	3	15	5	25	
Minimize Footprint	4	5	20	3	12	4	16	5	20	3	12	4	16	4	16	
Minimize Manning	2	5	10	3	6	4	8	5	10	3	6	3	6	3	6	
Minimize Maintenance	3	5	15	3	9	4	12	3	9	3	9	3	9	5	15	
Minimize Complexity	5	5	25	3	15	4	20	1	5	2	10	1	5	4	20	
Maximize Robustness	4	5	20	5	20	5	20	1	4	2	8	1	4	2	8	
Maximize scalability	4	5	20	4	16	5	20	1	4	1	4	2	8	2	8	
Maximize interoperability	4	5	20	4	16	5	20	1	4	1	4	3	12	2	8	
Total			200		135		174		98		91		94		138	
Fulfilment			1		0,68		0,87		0,49		0,46		0,47		0,69	
Ranking					3		1		6		8		7		5	

Camera stitching high volyme										
Criteroon	Weight	Ideal		Feature-based		Stereo calibration		Dynamic		
		v	t	v	t	v	t	v	t	
Maximize Target toleran	3	5	15	3	9	5	15	4	12	
Maximize Accuracy / per	5	5	25	4	20	3	15	2	10	
Minimize Process time	5	5	25	4	20	4	20	2	10	
Minimize Investment	3	5	15	4	14	5	15	5	15	
Minimize Footprint	3	5	15	4	12	2	6	4	12	
Minimize Manning	2	5	10	4	8	4	8	3	6	
Minimize Maintenance	4	5	20	5	20	4	16	5	20	
Minimize Complexity	2	5	10	4	8	2	4	4	8	
Maximize Robustness	5	5	25	4	20	3	15	2	10	
Maximize scalability	5	5	25	5	25	2	10	2	10	
Maximize interoperabilit	5	5	25	5	25	3	15	2	5	
Total		210		181		139		118		
Fulfilment		1		0,86		0,66		0,56		
Ranking				2		4		5		

camera stitching low volyme										
Criteroon	Weight	Ideal		Feature-based		Stereo calibration		Dynamic		
		v	t	v	t	v	t	v	t	
Maximize Target tolerance	3	5	15	3	9	5	15	4	20	
Maximize Accuracy / performan	5	5	25	4	20	3	15	2	10	
Minimize Process time	1	5	5	4	4	4	4	2	2	
Minimize Investment	5	5	25	4	20	5	25	5	25	
Minimize Footprint	4	5	20	4	16	2	8	4	16	
Minimize Manning	2	5	10	4	8	4	8	3	6	
Minimize Maintenance	3	5	15	5	15	4	12	5	15	
Minimize Complexity	5	5	25	4	20	2	10	4	20	
Maximize Robustness	4	5	20	4	16	3	12	2	8	
Maximize scalability	4	5	20	5	20	2	8	2	8	
Maximize interoperability	4	5	20	5	20	3	12	2	8	
Total		200		168		129		138		
Fulfilment		1		0,84		0,65		0,69		
Ranking				2		4		5		

A.3 Kesselring Matrices for Station Concepts

High-volume concepts									
Criterion	Weight	Ideal		H1		H2		H5	
		v	t	v	t	v	t	v	t
Minimize Process time	5	5	25	4	20	3	15	5	25
Minimize Cost	5	5	25	3	15	4	20	4	20
Minimize Footprint	5	5	25	4	20	2	10	4	20
Minimize Complexity	5	5	25	3	15	4	20	4	20
Maximize scalability	5	5	25	5	25	3	15	5	25
Total		125		95		80		110	
Fulfilment		1		0,76		0,64		0,88	
Ranking				2		3		1	
Low-volume concepts									
Criterion	Weight	Ideal		L1		L2		L4	
		v	t	v	t	v	t	v	t
Minimize Process time	5	5	25	2	10	4	20	3	15
Minimize Cost	5	5	25	5	25	3	15	3	15
Minimize Footprint	5	5	25	4	20	3	15	3	15
Minimize Complexity	5	5	25	4	20	4	20	3	15
Maximize scalability	5	5	25	3	15	5	25	5	25
Total		125		90		95		85	
Fulfilment		1		0,72		0,76		0,68	
Ranking				2		1		3	

A.4 Elimination Matrix

Elimination matrix for:								Criteria fulfillment: (+) Yes (-) No (?) More info needed	
Solution alternative	Solves main problem	Fulfils all demands	Compatible/Realizable	Reasonable cost	Safe	Fits portfolio	Enough information	Decision: (+) Continue (-) Remove (?) More info needed	
								Comment	Decision
H1	+	+	+	+	+	+	+		+
H2	+	+	+	+	+	+	+		+
H3	+	+	+	+	+	?	?	Shared FOV for radars is questionable at this stage	?
H4	+	+	-	?	+	?	?	Questionable to use dynamic approach in high-volume	-
H5	+	+	+	+	+	+	+		+
L1	+	+	+	+	+	+	+		+
L2	+	+	+	+	+	+	+		+
L3	+	+	?	?	+	?	?	Questionable approach for low volume	?
L4	+	+	+	+	+	+	+		+
L5	+	+	-	-	+	+	+	Not preferable to have both a track and station	-

A.5 Interview Questions

- 1. Can you describe your typical daily tasks and responsibilities at your station?**
- 2. Do you find the work at the station fulfilling?**
- 3. What do you think works well at the station?**
- 4. What do you think does not work well at the station?**
- 5. How do you handle any issues or malfunctions that occur during your shift?**
- 6. What are the key performance indicators or metrics you track in your role?**
- 7. What training or qualifications are required to work at your station?**