3D Layout Scanning for Smart Manufacturing
Method Development and a Study of Future Possibilities

Syed Z Ahmed
Vijay Nargund

Supervisor: Martin Hochwallner
Examiner: Mats Björkman
Abstract

The term ‘Industry 4.0’ leads to many new possibilities like smart factory which is the amalgamation of manufacturing systems in a network to perform tasks more efficiently. It is becoming more and more important for the companies to develop smart factories and integrate the devices within such a facility to meet the demands of the evolving market. The next generation production systems are designed to share the data within the network, plan, and predict the solution for the future problems.

One such technology under smart factory is 3D laser scanning resulting in point cloud of the production unit. The traditional way of documenting a layout is usually with the help of 2D computer aided designs which are susceptible to measurement errors and changes that are not updated regularly. With the help of point clouds, an as-is representation of the factories can be recorded which can be easily updated with changes in the real world. With advancements in virtual manufacturing, the need for visualization of the factories is increasing drastically. 3D Laser Scanning is one of the better ways of meeting this need, among many other applications.

The focus of the thesis had been to create a method document for 3D laser scanning of factories and to discuss the future possibilities of it. The research approach used in this thesis was conducting observational study, interviews and testing of the method. One such future possibility is autonomous scanning and how it would be beneficial for a company like Scania which is developing smart factories. Based on the study carried out during the thesis, a document presenting the method developed is included in the report. The report also points out the applications and benefits of point cloud over traditional layout planning methods.

Keywords: Digital Layout, 3D Laser Scanning, Point Cloud, Smart Factory, Industry 4.0, Layout planning, Virtual Manufacturing, Plant Service Bus.
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Syed Z Ahmed & Vijay Nargund

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<tr>
<td>AGV</td>
<td>Automated Guided Vehicle</td>
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<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
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<td>CNC</td>
<td>Computer Numerical control</td>
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<td>CPS</td>
<td>Cyber-Physical System</td>
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<td>EDA</td>
<td>Event Driven Architecture</td>
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<td>ESB</td>
<td>Enterprise Service Bus</td>
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<td>I4.0</td>
<td>Industry 4.0</td>
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<td>ICP</td>
<td>Iterative Closest Point</td>
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<td>IT</td>
<td>Information Technology</td>
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<td>LiDAR</td>
<td>Light Detection and Ranging</td>
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<td>NDA</td>
<td>Non-Disclosure Agreement</td>
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<td>PSB</td>
<td>Plant Service Bus</td>
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<td>RGB</td>
<td>Red Green Blue Colour Model</td>
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<td>SDK</td>
<td>Software Development Kit</td>
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<td>SOA</td>
<td>Service-Oriented Architecture</td>
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<td>VR</td>
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1 Introduction

1.1 Background
Industry 4.0 has led to the emergence of smart factories. The systems in such a factory are connected to each other to form a cyber physical system or a network of devices which makes the factory a flexible production unit as a whole. This then leads to smart manufacturing with the help of sensors and robots (Lasi, Fettke, Kemper, Feld, & Hoffmann, 2014). It helps in meeting the demand of the present as well as of the future. This ultimately leads to process optimization. Scania is on its way to developing such smart factories as the demand for sustainable and smart manufacturing is increasing.

Smart factory, in general, is the culmination of digitalization which 3D laser scanning is a part of. One of the applications of 3D laser scanning is layout mapping. In most of the cases, a single scan can’t produce a detailed image of an object and the reason behind it is explained in the later part of the report. This is a step closer towards smart factory. In the following chapter, the applications of 3D scanning are recorded. The scanned image can be used for various reasons ranging from visualization to using it in collaboration with virtual reality in the factory (Rex & Stoli, 2014). Integration of all the development will make the factories smarter and sustainable.

In the past, Scania has performed scanning operations but without following a proper methodology. The benefit of having a method document is to train the employees in a systematic manner so that they understand the function of each setting. The method document also includes post-scanning part of the whole process.

Scania is developing a digital factory layout. The scanned image will also help in designing the production system for the future. It will help in determining the correct position for the equipment, e.g. robots and CNC machines, before placing it. Also, safety in the work environment will be ensured.

Today, the focus of smart factories are not just on automation but also on ideas like connecting different production systems in the factory using agents (Leitão et al., 2016). This is where the role of Industry 4.0 comes in to the picture.

1.2 Smart Factory Lab at Scania
Scania Group is investing in the future technologies to develop the factories of the future. Smart factory lab at the Scania facility in Södertälje is a step towards accomplishing this vision. As the name suggests, the developments related to smart manufacturing are tested here. The lab, which is like a pilot plant, consists of an assembly section of a pedal car and involves the interaction of automated guided vehicle (AGV), virtual reality and other technologies for smooth operation of the plant. This project is to be implemented in different factories of Scania when it is ready.
1.3 Aim
The aim of the thesis was to create a detailed methodology to carry out 3D Laser Scanning of a factory area while considering various parameters and factors that might affect the efficient and effective utilization of the technology. The thesis also addresses the need for autonomous scanning and how to achieve it.

1.4 Research questions
The thesis aimed to answer the following research questions, in the mentioned order by achieving the goal.

RQ1: How is 3D layout scanning technology being used in the manufacturing industry today?
RQ2: How should Scania use the 3D scanning technology in the future?
RQ3: How can the scanning process be automated?

1.5 Delimitations
- The thesis would only cover one way of describing how Scania can use the 3D scanning technology, i.e. through a documented method.
- All the applications of point cloud was not explored in detail during the research conducted.
- Autonomous scanning will not be developed to implementation stage due to time constraint.
2 Theory

2.1 Industry 4.0

From the use of steam power to the integration of cyber physical systems in the manufacturing systems, technology has come a long way. This is what industrial revolutions have been about: bringing a change to the manufacturing processes. The fourth industrial revolution, otherwise called Industry 4.0 or I4.0, is an extension of the third industrial revolution in which the focus of manufacturing was shifted to automation.

The vision of Industry 4.0 is to connect all the parts and processes in the manufacturing industry together (Rüßmann et al., 2015). This thought has led to the emergence of concepts like smart factory and cyber physical system (CPS) (Lasi et al., 2014). CPS regulates the manufacturing processes with the help of agents. An agent in a CPS reacts to the demands of the situation in a production system. The agents get input from the sensors, analyze the situation on the basis of their system architecture and then respond accordingly (Leitão et al., 2016). It is one of the ways to connect the devices in a factory. Apart from CPS, Event Driven Architecture (EDA), explained later in this chapter, is another way of connecting devices. Increased production rate and lowered rejection volume are some of the benefits. Industries are aiming for creating flexible manufacturing systems so as to cope with the fluctuating change in demand. This results in shorter lead time. Generally, in a CPS more than one agents are involved. In this case of a multi-agent system, the agents interact with each other to produce an optimal response. The information is shared between the agents within a CPS which could be used as a reference in the future.

According to (Schwab, 2016), the fourth industrial revolution is evolving at an accelerated pace and technical competences will play an important role in the development of I4.0. Like every other revolution, it also has challenges and opportunities. Some of the most popular I4.0 initiatives taken are by China, Sweden and Germany. On one hand, Industry 4.0 has the possibility of improving the living standard and on the other it will lead to an increased gap between skilled and unskilled labour (Schwab, 2016). Thus, leading to greater disparity. As more and more automation is being introduced into the production sector, people are struggling to accept the change. There’s a fear that the demand for low-skilled jobs will decrease. On the bright side, Industry 4.0 will open the doorway for new positions for different skill requirement within an organization.
2.2 Smart Factory

The term ‘Industry 4.0’ leads to many new possibilities like smart factory which is the amalgamation of manufacturing systems in a network to perform tasks more efficiently (Lasi et al., 2014). Figure 2 shows a pyramid representing the levels of digitalization that can be achieved in the realization of a smart factory. Digitalization is a way of providing support to the manufacturing processes which starts with standardising processes and then connecting technologies through which data is gathered. This data is then analyzed by the system to predict responses and provide solution for a problem. Everything is connected with the help of a network. As explained by the authors of “The Smart Factory: Exploring Adaptive and Flexible Manufacturing Solutions”, “the key characteristics of U-Factory (which is a synonym for smart factory) are to be information transparency, autonomous control, as well as sustainable manufacturing” (Radziwon et al., 2014).

In other words, a smart factory is a solution for the manufacturing industry. It could help the production system in adapting to various problems arising during manufacturing with the help of cyber-physical system and its system architecture. This network of systems will shift the production system towards a more flexible and reconfigurable manufacturing system. Ultimately, other outcomes of this step are lean manufacturing along with low operation cost (Radziwon et al., 2014).

Some of the advantages of having a smart factory are uninterrupted networking of devices, seamless interaction of devices for quick problem solving, etc. Establishing smart factory is a means to optimize the manufacturing process with the help of sharing of information between different machines and the cyber physical system. This agile manufacturing system that can ‘predict’ and prevent’ is termed smart manufacturing. Smart manufacturing is designed to address the issues related to fluctuating demands(Davis & Edgar, 2011). One of the features of a smart
factory is that it will lead to less use of energy while manufacturing products (Shrouf et al., 2014). More and more companies are setting up smart factories in order to stay competitive.

The characteristics of a smart factory as described in (Shrouf et al., 2014) are:

- Remote monitoring
- Proactive maintenance
- Flexibility
- Mass customization
- Energy management

2.3 Digital Layout

The traditional way of documenting a layout is usually with the help of 2D CAD drawings which are susceptible to measurement errors, i.e. human error, and changes that are not updated regularly. To make sure the documented layouts are geometrically accurate and updated regularly, a so called “Digital Layout” needs to be developed (Lindskog et al., 2016). Digital Layout is a representation of a factory, usually in 3D, which includes all the geometrically accurate aspects and can act, with the right software tools, as a digital twin of the physical factory. A more dynamic version of a digital layout that allows simulations and real time tracking of the processes in the physical factory is the virtual layout (E. Westkämper, 2009). 3D laser scanning is a popular technology that is being explored as a tool to develop digital layouts.

2.4 3D Laser Scanning

3D laser scanner is a device used to capture the spatial data around itself and create a virtual representation with directional and distance measures of its surrounding environment (Lindskog et al., 2016). In this thesis the type of technology studies is terrestrial 3D laser scanning technology. It is based on LiDAR (Light detection and ranging), which is a technology where the device emits laser beams at objects in its line-of-sight and measures the distances based on the return of the laser beam. 3D laser scanners generally used in terrestrial scanning applications, collect spatial data and compile millions of points to form a point cloud (Klein et al., 2012). The distance measurements are generally achieved in either of two major techniques: time of flight and phase shift. Time of flight, as the name suggests, is a technique where the time taken for the emitted laser to reflect back is registered in order to calculate the distance measures. In phase shift technique, the device makes a comparison of the shift between the phases of laser beams emitted. Due to its accuracy\(^1\) and high point density\(^2\) in close range, it is normally used in scanning objects that are in a distance less than 100 m (Dassot et al., 2011)

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\(^1\) Accuracy refers to the correctness of the distances measured (ranges from millimetres to micrometres)(Dassot et al., 2011)

\(^2\) Point density refers to the spread of points in a given area(Dassot et al., 2011)
Figure 3 shows the principle method that a 3D laser scanner follows. As seen in the figure, the scanner can rotate 360° in the horizontal axis and a maximum of 320° in the vertical axis allowing it to scan all of its surroundings except the scan position. The scanner shown in figure 3 (FARO Focus 3D X) comes in two models of 130m and 330m ranges. Hence, depending on the size of the area to be scanned, a single scan or multiple scans (in most cases) can be made with different scan positions. In case of a single scan, only single side of the objects and surfaces scanned will be recorded. With multiple scans, a special process called as registration<sup>3</sup> is carried out in order to generate a single cloud of points.

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<sup>3</sup> Registration is a process to find the spatial relationship between multiple scans carried out at different locations which have different origins in the coordinate system (Inc., 2017)
2.5 Point Cloud
Point Cloud is a series of data points which when grouped together define the shape of an object. This technology has many applications ranging from the field of computer graphics to robotics. Point cloud represents ‘as-is’ portrayal of the surrounding in the virtual world which results in better planning and understanding of the shop floor in case of a production unit (Ruiz, 2017).

Figure 4 Point cloud of a part of a building

Some of the applications (Rex & Stoli, 2014) are mentioned below:

2.5.1 Visualization

Point cloud helps in visualization. It creates a very realistic virtual representation. The scanning helps in capturing the surrounding in a detailed manner in the form of point cloud. Thus, it becomes easy to visualize and observe. It could also be combined with the 2D layout of a building or a 3D model of a machine to study the differences. This aspect of point cloud is explained in detail in the result chapter. This creates the window for improving the layout and the success rate is thus increased (Lindskog et al., 2013).
The walkthrough mode enables the user to roam around in the area and look at the objects from different angles. But for this, multiple scans have to be performed from different locations capturing different sides of an object.

![Figure 5 Point cloud used together with 3D model](image)

2.5.2 Clash detection
Point cloud provides accurate representation of a factory layout. Therefore, it is easier to check and identify collision between built-in parts in the point cloud and a CAD model of new machine which is to be introduced in the layout. The suppliers could take the help of this technology to check if the machine could fit into the area before delivering it to the end customer.

2.5.3 Reverse engineering
The point cloud generated from laser scanning can also be used for reverse engineering. In order to perform reverse engineering, a manufactured part is taken and then scanned to generate point cloud. This point cloud will lead to a 3D solid model. It is otherwise known as surface reconstruction. The point cloud can be used to generate a 3D model of a machine as accurately as possible. It takes into account all the measurement of an object. This is helpful in case if the 3D model or documentation is absent.
2.5.4 Measuring the distance
The software in use, FARO Scene 7.1, has a feature which helps in measuring point to point distances as shown in figure 6. This becomes useful during reverse engineering process where it is required to know the dimensions of a 3D object.

![Figure 6 Point cloud used for measuring distances](image)

2.6 Registration
Registration is a process where the software determines the spatial relationship between the different scans and transforms them into a global co-ordinate system (Inc., 2017). Registration is carried out with the help of an algorithm; most popular one being Iterative closest point (ICP) algorithm. ICP algorithm looks for the common points between two scans in order to align them together (Walsh & Hajjar, 2009).

The latest registration software feature either a target less registration, where the scanner is positioned in various known coordinate points, or a target-based registration where artificial target objects with high reflective surfaces are used to combine matching point clouds. Since target less registration requires accurate placement of scanner to the required position, it is often not preferred (Becerik-Gerber et al., 2011). Targets are artificial objects in the scan environment that help the registration software match various scans together. Spheres are the most common type of targets that have a known diameter and has a highly reflective white surface as shown in the figure 7.
Often, it is important to survey the reference points using a Total Station\(^4\) before scanning for two main reasons. Firstly, it helps the registration process as the accurate sphere locations are known. Secondly, the scans are placed in a known coordinate system with known reference points (figure 7), which allows the user to manipulate the point cloud to the requirements. This will be explained in detail in the later chapters of the report. Surveying is carried out by a skilled surveyor as it requires competences and understanding in construction engineering.

2.7 Autonomous Scanning

As mentioned earlier in the report, CPS and EDA are some of the ways of having networked devices working together. The need to automate the process led to the study of EDA which is already in place at Scania.

Event Driven Architecture (EDA) is an architecture which defines how the different systems/applications interact with each other but it does not provide any response or store anything. One needs to design the architecture in a way that it becomes event driven and there is a possibility to store responses and establish connection to a decision-making system which can make decisions based on the responses received. This serves as a benchmark for making decisions for future actions in an efficient manner. Similarly, service-oriented architecture (SOA) is the amalgamation of different features within a framework. The use of SOA in businesses lead to a more flexible business model in order to meet the fluctuating demands of the market. The integration of applications will lead to better communication and sharing of the data between them (Keen et al.,

\(^{4}\) Total Station is an instrument that allows the user to measure the 3D coordinates of a point without direct contact in between them. (DITTA, M., & COLSON, 2017)
This is where Plant Service Bus (PSB), also known as Enterprise Service Bus (ESB), comes into the picture. SOA is an architecture that delivers services that is based on PSB.

As explained by Falko Menge, “An Enterprise Service Bus is an open standards, message-based, distributed integration infrastructure that provides routing, invocation and mediation services to facilitate the interactions of disparate distributed applications and services in a secure and reliable manner” (Menge, 2007). PSB is the infrastructure that provides support required for integration of different services within SOA (Keen et al., 2004).

In simple words, a company may run many applications, as explained above, depending on the department and varying from one department to the other. These services could be provided by third party companies or by one of the departments within the company. In such situations sharing of data within the company becomes an integral part of the organization. It is impossible to develop a single application to cater to the needs of all the departments. All these applications are assembled together with the help of PSB (Menge, 2007).
3 Research Approach

A major part of the thesis was to develop a method to carry out 3D laser scanning for the layout which answers the research question 2. In order to be able to do this, it was important to first determine the current state. The current state here refers to the usage of the 3D laser scanning technology in a production context. This was done with the help of a detailed literature study and interviews with experts, which answered the research question 1. As a solution to ease the updating of scans regularly, automation of scanning process was studied and tested to a certain level. This answered the research question 3.

Figure 8 represents a flow chart of the steps taken in order to carry out the research in this thesis. Each of these elements and how they helped in the research are explained in detail in this chapter. The result chapter is intended to explain the outcomes of the elements shown here.
3.1 Literature study
This step formed the basis for the thesis. Theoretical knowledge was gathered from academic articles, journals, etc. And a study about Industry 4.0 and 3D laser scanning was done. This led to the identification of the importance of a smart factory in the current industrial revolution. Careful study of laser scanning brought forward the aspect of autonomous scanning which is currently covered by the scope of the thesis.

3.2 Interviews
There are different ways of gathering information, like conducting interviews or online surveys. The purpose of doing it is to gather raw data. It forms a part of the development phase because the product specifications are somewhat dependent on the needs of the stakeholders. Documenting the interaction with the stakeholders can be done in the form of audio recording, video recording, notes or still photography, to name a few. In the end, the result is a set of raw data.

Some of the forms of interaction are explained below:

- **Audio recording:** This is easy to do but then writing it down or transcribing it for the report is difficult as it takes time.
- **Video recording:** It is a useful way of observing and recording data from the stakeholders, like the users, in their work environment. It can also be used sometime later to explain it to new members in the team. It also helps in identifying customer needs that might appear later.
- **Notes:** This is the most common form of documenting data from the users. It is in the form of handwritten notes that are recorded during the interview. The interviewers later discuss it between themselves to interpret it into the needs of the stakeholders.
- **Still photography:** It is pretty much self-explanatory. This is helpful in capturing the work environment but sometimes the organization doesn’t allow photography inside. So, this is one of the least used form.

(Ulrich & Eppinger, 2003)

Apart from the above described methods of conducting an interview, there are three different types of interviews:

- **Unstructured:** This type of interview is led by the participant in a narrative way. The interview is not restricted in the form of a set of questions.
- **Semi-structured:** It is a way in which the interviewer doesn’t necessarily have to adhere to the set of prepared questions. The responses from the participants determine the direction in which the interview will head.
- **Structured:** Here, the interviewer asks questions from a standardized list of questions that he/she must have prepared it beforehand. It doesn’t involve deviation from the list of questions as they are specific to the topic.

(Longhurst, 2003)

The authors went ahead with the unstructured form of interview along with audio and video recording. It was chosen to do so because of the time constraint for the interviews. The questions/topics discussed in the interviews are listed in Appendix I.
3.3 Participant Observation

Participant observation is a method of collecting qualitative data to understand the activities carried out by a person/group through a combination of participation and observation of the activities. Participant observation serves as a tool to put the theoretical study to test and validate it. By combining participant observation with interviews, video observations, notes and so on, a strong understanding of the concept can be achieved (Kawulich, 2005). To conduct a successful participant observation, it is important to understand in theory, the process being researched and be familiar with the site where the research is being carried out (Mack et al., 2005). Participant observation method was used during the initial study conducted explained in more detail below.

3.4 Scanning at KTH Södertälje

To attain practical knowledge about 3D scanning technology, the authors conducted a participant observation to collect qualitative data about the work flow involved in conducting 3D scanning in a factory. The scanning was carried out alongside a consultant from Virtual Manufacturing AB, who provide 3D Scanning services to manufacturing companies. The scanning was carried out in two rooms at KTH Södertälje campus where the smart factory lab was moved temporarily. The notes and the observations recorded through participant observation method during the scanning has been used to document the method to be followed to conduct 3D scanning in a factory based on purpose and requirements of the scanning. In addition to participant observation, an unstructured interview with the consultant from Virtual Manufacturing AB (Refer Appendix I) was also conducted to understand important factors to consider in the scanning process.

This was followed by a non-participant observation of the processing workflow carried out on Faro Scene, by the consultant from Virtual Manufacturing AB. The authors made use of video and audio recordings to document the workflow involved to be able to repeat and confirm the same. With this data, the processes were repeated with the raw scans to make a comparative study with the finished deliverables from Virtual Manufacturing AB before developing the method.

3.5 Processing of data

After the scanning workflow was studied at the KTH Södertälje campus using participant observation and interviews, the next important part of the method, processing of the scan data was to be studied and the optimum method to get the best result was to be developed.

In this thesis, the registration software used is FARO Scene 7.1, which is a software provided by the manufacturers of the Faro Focus 3D. In addition to this, AutoCAD is also used to match the point cloud with the pre-existing 2D drawings of the layout scanned at KTH Södertälje.

The method being developed delivers a solution to scan the factory, process the scans and match the scans to the 2D drawings. In order to put together a work flow for this purpose, the scans carried out at KTH Södertälje are processed in the software Faro Scene. This helped the authors to familiarize themselves with the software. Some of the important functions provided in the software are to edit the point cloud to clean unwanted points, manually register wrongly registered scans
and placing the scans in a previously known coordinate system. After the processing of the scans is completed, the project can be exported into a number of file formats based on the purpose. In order to be able to compare the point cloud to the 2D layout drawing, the point cloud was converted to ‘.rcp’ file format which is an Autodesk ReCap file compatible with AutoCAD.

3.6 Study visits

Observational study proved to be an excellent approach to understand the 3D laser scanning technology and the process. However, some of the data collected had a scope to be improved or verified with expert opinions. Therefore, it was necessary to conduct visits to observe the successfully implemented scanning method at Volvo Cars and listen to the doctoral research carried out in this field by the doctoral candidate at Chalmers University of Technology. The intention of the visit and the experts interviewed are mentioned in table 1 below. The questions and topics discussed in these interviews are presented in appendix I.

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<th>Place of visit</th>
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<th>Experts interviewed</th>
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<td>Doctoral candidate (Chalmers)</td>
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<td>CTO, ATS Advanced Technical Solutions AB</td>
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<td>Volvo Cars Torslanda, Gothenburg</td>
<td>Discussion of 3D scanning method and applications used by Volvo Cars</td>
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<td>Method Developer (Volvo Cars)</td>
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</table>

3.7 Scanning at Scania

This stage of the thesis required using the Total Station for surveying in conjunction with the scanner and testing the method document. After a discussion with the supervisor at the company, it was decided that the future smart factory area at Scania should be scanned. This area was selected since major overhauling of the area was required for setting up the smart factory. Since it was going to be the new smart factory so fixing the precision washers on stable and fixed elements, like pillars, was an important part of this process. It was agreed that the usage of point cloud for this area could prove beneficial as it could be used for better visualization. The scanner was rented from

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5 Precision washers are metallic objects that are used to place the targets, i.e. spheres. These are fixed on permanent elements, like pillars, so that it could be used for scanning the layout more than once. The targets are placed on top of these washers.
Mitta AB for a period of 10 days. The processes followed are explained in the form of the steps below:

- **Step 1:** This step helped in setting the priorities straight as the floor and the walls were given importance. Walking through the scanning area was done during the weekday and the scanning group returned to the area later that day after the working hours to clear the area. Many objects had to be moved out of the scanning area to capture as much floor area and the wall as possible.

- **Step 2:** A weekend was chosen for scanning as the production unit was expected to be shut down and no workers were supposed to be there. The scanning group received a personnel from Mitta AB who came along with the total station to help out with the surveying and reference points. When walking through the scanning area, the scan positions and target placements were decided according to which the washers were placed. The scan positions were marked with tapes on the floor. While fixing the washers for the targets, one should keep in mind that the laser from the scanner should be able to reach the targets. This becomes useful while performing registration.

- **Step 3:** The scanner was placed at the first scan position and the targets were placed in such a way that they were visible to the scanner. After turning on the scanner, the group had to move away from the scanner so as to be outside its range and the field of vision or else distorted points of a moving person would have appeared in the point cloud during the registration process.

- **Step 4:** After the scanning was done, it was time for processing the point cloud and cleaning the image. For this, FARO Scene 7.1 was used. The steps for scan data management is explained in the method document (appendix II). This step also included importing the surveyed data (.csv file) to Scene 7.1. These reference points are to be used. This step helped in writing about the “Scan Update” part in the method document.

### 3.8 Testing the method document

In order to evaluate the method developed after examining the data collected during the scanning at KTH Södertälje, a test scanning had to be performed at the future smart factory facility at Scania’s premises. The test scanning was carried out by a Project Engineer at the Digital Factory department with experience in layout planning. There was no detailed pre-study carried out by the participant regarding the scanning process which allowed the authors to evaluate the improvements to be made to the method. The evaluation of the method was done for three aspects of the method, namely, planning the reference point positioning, planning the scan positions and choosing the settings on the scanner (refer appendix II). Qualitative data were collected through non-participant observation, meaning the observers, in this case the authors only observed the participant and did not take part in the process themselves. Also, an unstructured interview to obtain a feedback from the participant. The observations were recorded in the form of notes which was later used in making improvements in the method.
The flow of activities during the evaluation was as follows:

a. First, the participant was made to read through the method document and present his interpretations to the authors. This was done to analyze the understandability of the developed method. The intended result was to determine the level of detail required in the work flow.

b. After the initial read, the participant was allowed to carry out the scanning while “thinking out loud”. This further allowed the authors to determine the difficulties faced by the user when using the method for the first time. This also showed the dependability level of the method document.

c. The observations made from the evaluation of method were recorded and the improvements to be made were incorporated in the method document.
**4 Result**

4.1 Workflow Documentation for Scanning

The first part of the method development for scanning was to determine a standard workflow for the physical work involved in scanning. The scanning at KTH Södertälje, as mentioned before, was the observational study used to learn the workflow involved. This initial study resulted in documenting the workflow in the following categories of work:

a. Setting up the equipment  
b. Planning of reference targets  
c. Planning of scan positions  
d. Choosing the right settings  
e. Starting the scan

The above steps are explained in detail in Appendix II. The steps were later changed in order to improve the method. In addition to the workflow documented, some of the important factors to consider while scanning were also documented to improve the quality of the results from following the method.

The interviews conducted with the consultant from Virtual Manufacturing AB led to determining the factors affecting the resulting scans. Also, the optimum settings, in the context of a production facility was formulated from the data collected through the interviews and the observations. Table 2 shows the suggested values of settings, taken from the method document (Appendix II). However, these are subject to changes based on the area being scanned and the requirements of the scan quality. Some of the exceptional cases are considered and shown in table 2 as well.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Suggested</th>
<th>Exceptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profiles</td>
<td>Indoor ..10m</td>
<td>If objects of interest are too far from scanner, choose Indoor 10m.</td>
</tr>
<tr>
<td>Resolution</td>
<td>¼</td>
<td>If there are lack of targets and they are far from the scanner, choose higher resolution</td>
</tr>
<tr>
<td>Quality</td>
<td>2x-3x</td>
<td>N/A</td>
</tr>
<tr>
<td>Scan range</td>
<td>Default</td>
<td>If you do not need details such as pipelines on the ceiling reduce the vertical range</td>
</tr>
<tr>
<td>Sensors</td>
<td>Keep everything ON other than GPS</td>
<td>N/A</td>
</tr>
<tr>
<td>Colour settings</td>
<td>Even weighted Metering</td>
<td>In case of low lighting, use horizon weighted metering to capture maximum light possible</td>
</tr>
</tbody>
</table>
4.2 Processed point cloud of KTH Södertälje

The scans carried out at various scan positions at the KTH Södertälje building were processed and registered together into a single point cloud on Faro Scene. The major outcome of this result was to study the features of Faro Scene and understand the work flow involved in create a registered point cloud. Additionally, the transformation of the point cloud to a known coordinate system was a challenge that the authors set out to solve. In the case of Scania, all the 2D layout drawings and 3D CAD models related to layout correspond to their building’s coordinate system. Therefore the optimal solution is to have the point cloud also to match this coordinate system to maintain a standard.

The isometric view of the resulting point cloud after cleaning up of unwanted points is shown in figure 9. This point cloud is a result of registering 12 different scans taken at various positions inside the building. The scanner provides the option scanning with color. This is done by capturing images of the scanned area, whose RGB properties are later applied by Faro Scene. Faro Scene also provides an option to either have the point cloud in color or greyscale. The method document in appendix II describes more about this feature and how to use it. In figure 10, one of the scan positions is shown with a closer look at the point cloud from the inside. Each of the scans are placed in its local coordinate system immediately after the scan with the scanner’s position as the origin. In figure 10, this scanner position is the center of the scanner shown. With the help of Faro Scene, the 12 scans were registered together into a single point cloud. Processing of data attained from scanning at KTH Södertälje was used to study the flow of operations carried out in FARO Scene to get the resulting point cloud shown in figure 9.

A summary of operations to be carried out in Faro Scene are:

a. Creating a new project and importing the scans
b. Processing of scans
c. Automatic/Manual Registration of scans
d. Verification of targets and scan placements
e. Transformation of point cloud coordinate system
f. Exporting the project point cloud to required file format

These steps are described in detail with the help of pictures in the method document in appendix II.
Figure 9 Point cloud of KTH Södertälje

Figure 10 Example Scan position
4.3 Comparison with 2D Layout

In order to be able to bring together various layout support documentations like 2D layouts, 3D layout models, VR scenes and also point clouds, it is important to have these representations in a standard reference system. Therefore, it was essential to answer the question of transforming the point cloud to a known coordinate system on Faro Scene.

This transformation also helps realizing one of the important applications of point cloud is to visualize the factory environment as-is. There are several problems with using only 2D layouts; missing important details such as pipelines and pillars, lack of understanding of the 2D layout by everyone involved in the layout planning process, irregularity in updating the layout and so on (Lindskog, 2018). A few of these problems are easily tackled by the use of point clouds. In the figure 11, an illustration of how point clouds can used in combination of 2D layouts to achieve a visualization of as-is environment can be seen. With the help of this, the walls, pipelines, pillars and other structural components normally absent in 2D layouts can be pictured which helps in planning the changes in layout without being on-site. Figure 11 shows the point cloud previously presented, overlapped with the 2D layout by transforming the coordinate system of point cloud to that of the 2D layout.

![Figure 11 Point cloud matched with 2D Layout](image)

4.4 Updating the scans

As mentioned earlier, 3D laser scanning creates point cloud which could be used for various applications. In a production unit changes occur continuously and on a regular basis depending on the demand and the decision taken by the management. This makes the production floor cluttered with little space between the objects. The need to update the scanned data arises from the orderly change in the floor plan or placement of new machines. The main motive behind scanning any structure, among many others, is to have an "as-is" representation of the real world. Therefore,
Updating the scans of the whole floor or part of it is necessary. If the floor plan has changed for a part of the building then it is advised to scan that particular area and not the whole building. The reason it is instructed so is because of time constraint because 3D laser scanning is a tedious process. Also, because the scanning method in discussion here is expensive.

Updating the scans do not require surveying of the area again if surveying was done before the initial scanning. The user has to just scan the factory and replace the old scans with new ones. The detailed process is explained in the method document attached in appendix II.

4.5 Autonomous Scanning

With the help of the literature study and the understanding of the current use of the scanner it was concluded that autonomous scanning could be a great way to scan production facilities. Autonomous scanning is to be performed with the help of an AGV and plant service bus (PSB) in combination with the scanner.

The software development kit (SDK) to develop applications to control the scanner was obtained from FARO. The license to use this SDK for development is provided by the company on signing a non-disclosure agreement. The role of the SDK is to give more control to the user while accessing the scanner remotely. With the help of the SDK, the storage location of the scan files can also be changed to a desired location. This feature allows the FARO scanner to send scan files, after the scanning is done, to the connected computer. The programming language used for the SDK was C#. The role of each statement in the code was explained in the FARO SDK manual that the group received from the company on signing the NDA.

The function of some of the statements from the C# code are explained below:

1. The user can provide a waiting time for the scanner to get connected to the computer.
2. The storage location for the scans can be changed with the help of the SDK. The files can be stored in the computer instead of the SD card inside the scanner.
3. Presence of the loop in the code helps in checking the scan progress. If the scan progress is 100%, i.e. scan completed, the program exits the loop and prints “Scan Completed” as an output for the user.

In order to make autonomous scanning work, the scanner should be connected to the PSB and the PSB to the AGV, on top of which the scanner is supposed to be mounted. Communication is the key for this concept to work. The AGV should communicate with the PSB on reaching the scan positions so that the PSB could further communicate with the scanner to start the scanning process. Once the scanning process has been completed for a particular location, the PSB will receive the “scan completed” message which will be an indication for the AGV to move to the next scan location thereby reducing the time and labor required for scanning.
The problem with the current setup is that there needs to be a connection or a bridge network between the PSB and the scanner because of the hardware restrictions of the scanner. The scanner can only create a network of its own for a computer to join and unfortunately, there is no option for the scanner to join the Scania network to get connected to the PSB. This is something that might require a collaboration between Scania and FARO. In the current setup, the AGV in discussion is already connected to the Scania network and is communicating with the PSB.

For the above-mentioned task, a representation of the surrounding, in the form of a map, is to be fed to the AGV. The map will contain information about the obstacles in the path and positions for scanning.

Successful implementation of this concept will contribute to updating of scans autonomously, i.e. with the help of the AGV. It has to be noted that the step called “scan data management” has to be done manually as per the need of the user.

4.6 Evaluation of the method document
After the method was completed, it was put to use and evaluated through a non-participant observation by the authors. This helped the authors improve the method document and determine the usability of the document. Some of the difficulties observed during this study were:

- Instructions on planning scan positions not clear
- Unable to determine “Where to start” the process
- Reasons for some steps not explained clearly
- The types of scanners the method is valid for not mentioned
- Settings of scanner not explained well

These observations made were used to improve the method which can be found in Appendix II.

4.7 Method documentation

The method for planning and carrying out 3D laser scanning, processing the scans and transforming the point cloud coordinate system was developed based on the combination of the literature studies, interviews, on-site study of the scanning process and evaluation of the software used to register the scans. Documenting the studies carried out in the thesis formed the basis for developing this method.

![Method steps diagram](image)

Figure 13 Method steps

The method was classified into three different steps: Initial Planning, Scanning and Scan Data Management as shown in the figure 13. The first time a plant or an area of interest in a plant is being scanned, there is a need to follow all the three steps. This is because of the absence of surveyed reference points. However, to update a scan or a few scans in the point cloud because of the changes in the scanned area, only the “Scanning” step and parts of “Scan Data Management” needs to be followed.
The step “Initial Planning” deals with the planning of reference point position and surveying them. This part of the method is essential to ensure easy usage of the resulting point cloud. With the surveyed reference point, the point cloud is placed in a referenced coordinate system. This allows the user to:

a. Refer any new scans to this referenced coordinate system by importing the .csv file of the reference points (Figure 14).

b. Ease up the registration of scans on FARO Scene by automatically recognizing the reference sphere centers, i.e. reference points.

c. Skip the transformation of the new scans to a known coordinate system

In figure 14, `A100` is the name given to the reference point whose x, y and z coordinates are 229.1098, 100.1224 and 2.9274 respectively.

The “Scanning” step deals with the field work involved in the scanning. Here, a step-by-step workflow involved like planning out the scan positions, the placement of targets and the settings to be chosen in the scanner are explained in detail.

In the “Scan Data Management” step, the work instructions for using Faro Scene to register the scans are listed out. Some of the functions such as cleaning up the point cloud by deleting unwanted points is very important to place the scans correctly. This step also explains ways of importing surveyed points to place the scans in the reference coordinate system. Further, the procedure to calculate offsets to move the reference coordinate system to a known building coordinate system is also explained. Several layout and virtual manufacturing tools at Scania correspond to the building coordinate system, including the 2D CAD drawings, which demands for point clouds to follow the same.
In “Scan Update”, instructions to follow while updating a section of the previous point cloud is explained. This of course involves the steps “Scanning” and parts of “Scan Data Management”.

For a detailed information on the above mentioned steps, refer to the method document presented in Appendix II.
5 Discussion
5.1 Results
The research carried out in the thesis contributed towards results that can be divided into two parts; development of a method and assessing the possibility of autonomous scanning. These results are discussed below in detail.

5.1.1 Method document
The method developed in the thesis serves as an efficient step towards the structured implementation of 3D Scanning technology in Scania’s production and logistics. The conception of this thesis was due to the need to document this developed method and the scope of the thesis was limited to this task initially. Although the technology has been investigated several times at the company by various departments, there has not been advancements in efficient use of the same. This could be changed with the help of the method.

Documentation is an effective way to present the method, which the authors feel will serve the purpose. The steps explained covers the delivery of the point cloud in an immediate usable form. The resulting point cloud can be used for visualization of the shop floor, verification of machine installments or as a layout planning tool. The document however does not include the storage options and methods for the point clouds. Comparison of cloud and client-based storage of the files has to be further investigated and the most viable option for Scania must be selected.

Evaluating the method document helped us determine the potential challenges that could be involved in training engineers in learning the right way to perform 3D Scanning. When choosing the reference point positions although the instructions are clearly explained, we found that it is difficult to follow all the instructions right the first time. The scan positions and reference points positions are interdependent with each other which challenges the user to proactively think of the whole process. Therefore, we found that not every instruction and tactic involved in this process could be expressed in a documented manner. The user would still need to train himself to use the technology well by experimenting different possibilities and studying the resulting point clouds. This makes 3D scanning an iterative learning process.

Compared to the scanning process, managing of the scan data is easily understood and unequivocal. In the chapter, Scan data management in the method document, the workflow to go from “raw scans” to “referenced point cloud” is explained step-by-step using pictures to support the understanding. The document simplifies several steps which in reality required vast research and conversations with the experts in the field. The application of 3D scanning in the manufacturing industry is still a developing technology and the companies are striving towards achieving a maturity of this technology which would require much lesser competence to use. Currently, it is important for the user to be able to understand the coordinate transformations and the way the point clouds generated by the scanner work with coordinates. We feel that this can be simplified by providing a more user-friendly functionalities in FARO Scene to work with transformations.

The document serves the purposes of guiding a production engineer carrying out scanning for the first time. However, it becomes more efficient if an experienced user is present to provide assistance. It can also be improved with the help of video tutorials.
5.1.2 Autonomous scanning

The concept of autonomous scanning described in this report outlines the significance of 3D laser scanning to be performed in a more efficient way. Autonomous scanning and its importance discussed in the report addresses one of the research questions which is aimed at automating the process. The reason why the authors felt the need to do this is because of:

- Time-constraint
- Inefficient human resource utilization

3D laser scanning of a production unit takes up a lot of time depending on the layout of the building and the complexity of the design and placement of machines. Since Scania is planning to scan these production units and update the point cloud so scanning it manually and hiring a personnel to do the job seemed unwise.

In order to check the viability of the concept, interviews were conducted which led to discussions about the future possibilities in the manufacturing industry. To further develop the concept, it is recommended that more information is to be gathered as the idea of the bridge network has to be implemented. The authors couldn’t set-up the bridge network because of limited time-period for the thesis but were able to remotely control the scanner without linking it with the PSB. For this idea to be a success, cooperation with the IT department is needed.

A challenge for the future work could be the non-availability of the scanner with the department. For the thesis work, the scanner was rented from external companies. Therefore, proper planning and implementation was a major part of the thesis as the authors had to do the first scan as observing participants and understand the whole process of laser scanning from the consultant from Virtual Manufacturing AB. The authors would like to suggest to the company that they should look into this matter if they decide to adopt point cloud technology for ongoing as well as future projects.

5.2 Research approach

The research approach followed in the thesis was effective to answer the research questions that were formulated. The combination of observational studies, unstructured interviews and study visits gave us a detailed understanding with respect to the means of using 3D scanning technology in manufacturing.

The observational study of the scanning and post processing of scan data carried out at KTH Södertälje resulted in the understanding of the workflow. Along with this understanding, the study also led us to determine some of the challenges which we were unaware of, during the pre-study involving literature study and interviews. Although at the time, processing of data seemed as a simple process because of the user friendly interface of FARO Scene, practically evaluating the tools in the software provided more challenges in Scania’s context. Challenges such as:

- Matching the coordinate systems of the point cloud to the one used as standard at the company for other visualization and layout planning tools, and,
- Difficulties related to updating of scans,
would not have been recognized without the help of the study carried out at KTH. This provided a good foundation to start working towards the method.

The literature study carried out for the second time helped to get a better understanding of how the coordinate systems are decided and manipulated with respect to point clouds. In addition to the literature study, study visits to Chalmers University of Technology and Volvo Cars helped us understand the important steps to follow to ensure the method’s usefulness in a long term. We also discussed the ideas and potential of automating the scanning process to make the updates of scan more efficient and effective.

Although an evaluation of the method was carried out, it was mainly concentrated on the manual work involved in scanning and not the processing procedure. A better evaluation method would have helped better to determine the usability of the method.

5.3 Future work

The applications of point cloud technology and the method followed for 3D Scanning at Volvo Cars, were a major part of the discussion with the experts at Volvo Cars, Torslanda. During the meeting different aspects of the technology was discussed as the authors tried to gather as much information as possible. Volvo Cars have been using this technology for quite some time now and the methods used by them were an inspiration in the development of the method in this thesis.

The authors would like to recommend Scania to have a designated team for scanning for efficient use of the resources. This team could provide support for scanning when needed. Although the goal in the future would be to autonomously scan, the scan data management will still rely on personnel for processing and registration. Automating these steps could be a possibility which could be met with collaboration with the scanner company.

The accuracy of point cloud is commendable which led to questioning the reliance on 2D layout drawing where the measurements are taken manually and are prone to mistakes. Also, they generally do not include the three dimensional measurements of the shop floor. 2D layout drawings are not completely understandable if the person does not have the right competence. Using 2D layout drawings in combination with 3D point clouds would serve as an excellent visualization tool. It also helps to recognize major errors in the 2D layout drawings. Although we do not expect 3D point clouds to replace 2D layout drawings as a layout planning tool, there is a great potential of using them as an additional tool.

The way Volvo Cars have been using this technology is praiseworthy. One of the things talked about during the visit to Torslanda was storage and accessing of scans. This was not a part of the thesis but it would be helpful for Scania to use cloud services similar to “Scene WebShare Cloud” to share point cloud files within the Scania network. With the help of cloud storage services, all the scan files and projects could be stored at one place and made accessible to Scania employees all around the globe. Here again, cooperation with the IT department and compliance with Scania’s security codes will be needed in order to get a more definitive result.
Some of the problems faced during this thesis are:

- Non-availability of documentation from previous scan methods at Scania
- Not having a standard reference system for point cloud

For the future, the authors would like to advocate for a careful study about the applications of point cloud and having the reference system defined with the help of a total station for all the buildings to be scanned. Before scanning the production units, the technology has to be tested in a pilot plant.

5.4 Ethical value of the research
A production unit, like one of Scania’s, is occupied with people on the shop floor during work shifts. As mentioned earlier in the report, laser scanning is a tedious task and is made even more difficult with the presence of personnel as they have to be removed from the point cloud during the scan data management step. This could be solved by autonomous scanning. Through the implementation of autonomous scanning it is believed that it will be easier to scan shop floors and store and manage point cloud. The idea is to scan the shop floor after working hours, with the help of AGV, so that it does not have any effect on the production capacity of the plant. Also, a scanner in the production unit might attract some workers while it is in operation. This could be harmful for them as the scanner emits laser beams. The authors were faced with such situation while scanning the layout and had to warn the passersby. Consideration of the work environment was important for this thesis as the authors believed in decentralization of these processes. A successful implementation of 3D Scanning technology will lead to employment opportunities in several areas of competence as it demands for an interdisciplinary research and development.
6 Conclusion

3D Laser Scanning technology has been around for quite a long time in construction, mining and forensic applications. For several years, major manufacturers have found the potential of this technology in virtual manufacturing world. The point clouds produced through 3D scanning are being used in the industries to verify installments of machines, plan layout improvements and in Virtual Reality (VR) where an as-is representation of the factory plays a big role. Although currently the major applications of point cloud are related to visualization and inspection purposes, more and more opportunities are being identified every day.

The method developed in the thesis provides means to use the technology systematically. The main challenges tackled such as establishing a reference coordinate system, finding a standard procedure to process the scans and a viable solution to keep the point clouds updated will add a great value towards implementation of the technology. The method would further encourage more engineers to gain the skills to carry out 3D Scanning and spread the competence in the company. This will also lead to a greater recognition of the usefulness of the technology in various areas of Scania. However, there are further challenges to be solved as the implementation is carried forward. Some of the main tasks would be dividing responsibilities among the resources, designing a good way to store and share the point clouds and establishing reference systems in all the facilities the overall scanning process.

As the aforementioned tasks are handled one by one, the need for automating the technology keeps rising. Therefore, it is a good idea to start working towards the possibilities of autonomous scanning and the research question 3 was aimed at answering the same. The work carried out in this thesis was a stepping stone towards starting the research towards automating the 3D Scanning process. The authors were able to explore the features and abilities in the current technology that would facilitate automation. A promising concept was developed and part of this concept was also tested. Although there are ways of achieving a solution to automate the process as explained in the thesis, in order to be able to develop an implementable solution, the authors feel there needs to be improvements made in the hardware capabilities of the scanner. In future, this can be better achieved by collaborating with FARO.

With applications evident in several areas of manufacturing industry, 3D Laser Scanning is a technology that is here to stay and prosper. A standardized method development and its continuous improvement is essential to effectuate its total contribution to the future of smart manufacturing.
7 References


8 Appendix
8.1 Appendix I: Interviews

1. Consultant, Virtual Manufacturing AB
   - What are the factors to consider while planning sphere positions and scan positions?
   - What are the optimal settings to choose for factory scanning context?
   - What is the purpose of using survey points? How does it help updating of scans?
   - What happens during the registration process in FARO Scene?
   - What are optimum conditions of the environment to be scanned, for example, lighting?
   - How does other brands of scanners fair with FARO scanners?
   - What do each of the settings on the scanner mean?
   - How is the transformation of point cloud to a known coordinate system done?
   - What are the tools available on FARO Scene to delete unwanted points?

2. Doctoral Candidate (Chalmers University of Technology)
   - What are the limitations of 2D CAD representations of layout?
   - How does a total station measure the reference points?
   - What is your opinion on autonomous scanning? Have you researched or worked with this?
   - Can there be one standard method to carry out scanning?

3. Senior Advisor and Method developer, Volvo Cars
   - What does Volvo Cars use point clouds for? How long has it been used?
   - How are the responsibilities divided for scanning (for example between scanning, postprocessing, data handling and so on)?
   - How is the reference system for the point clouds established?
   - What needs to be improved in this technology?
   - Is Volvo Cars looking into automation of 3D Scanning process?
8.2 Appendix II: Method Document

Method Document for 3D Scanning
Cover: FARO Focus 3D Scanner (Image taken from: FARO Focus)
Terminology

1. **Reference point**: A point in the facility which is surveyed with a total station, the center of a reference sphere in most cases.

2. **Precision washers**: Circular metal washers glued to the pillar/column to mark the reference point.

3. **Targets**: Artificial objects mounted or affixed at the reference point which will help the registration of scans to form a point cloud.

4. **FARO Scene**: Scan Registration software by FARO Technologies.

5. **LayCAD**: Autodesk CAD software package for layout planning at Scania.

6. **Project point cloud**: A FARO Scene project file with all the points in a scan project.

7. **Scan**: In FARO Scene, a scan is a scan file as recorded by the scanner with spatial and color data of millions of points.

8. **Scan project**: In FARO Scene, a scan project contains all details of the project including the workspace, project revisions and the project point cloud.

9. **Scans**: In FARO Scene, Scans is a folder in the workspace in structure tree containing all the scan files.
Introduction

3D Laser Scanning in a production context comprises of various steps which demand understanding and competence in production engineering, layout design and even parts of construction technology. This document aims to serve as a guide to using this technology in a systematic and standard manner. The procedure is explained in 4 different sections; Initial planning, Scanning, Scan data management and Scan update.

This document is valid for the use of Faro Focus laser scanner and Faro Scene Registration software. Although most of the important activities involved in the use of 3D Scanning technology in production are described in this document, it is advised to refer to the Faro Focus user manual to be familiar with the equipment functionality and safety instructions. In addition to basic knowledge about point cloud, knowledge to use LayCAD is required for some of the steps of the method.
Initial planning

This chapter explains the preparations that are needed to be made before starting the scan procedure for the first time in the given facility. This involves planning of reference point locations and surveying the same points. Surveying is the science of determining the 3-dimensional positions of points, i.e. the distance and angles between them. Surveying is required for two main purposes in the scanning context:

1. Surveying makes registration of different scans together in Faro Scene much easier since the positions of reference spheres will be known.
2. Surveying helps us define our own co-ordinate system for the point cloud which we can manipulate to use the point cloud in CAD software and other applications.

Figure 15 Placement of a washer on a pillar

Figure 16 Fixing of a prism to find reference point
1. Plan the reference points

- Reference points are surveyed points in the facility where the targets will be fixed during scanning. These are surveyed using a total station which measures the center of the prism as shown in figure 16 which is the same as the center of a reference sphere.
- Targets come in 3 types: spheres, checkerboards and markers. In a factory environment where there are equipment, machines and other objects, spheres are the best targets as their circular surface allows it to be recognised from any angle. Spheres normally are of two different sizes. Pay attention to the size as this needs to be specified in Faro Scene during registration.
- To plan the positions of the reference points, it is advisable to have the 2D CAD drawing of the facility to ensure optimum spread of the reference points. But it is also important to be at the place to make sure the reference spheres that will be placed at these reference points are not obstructed by obstacles in different lines of sights which requires the user to be at the facility.
- Plan the reference point positions by being at the facility while having the 2D CAD drawing to plan out the spread.
- The goal is to cover as much area as possible with the reference points. The distance between two reference points should depend on the range of the scanner that will be used.
- Reference points must be selected on stable objects in the environment, like pillars and columns.
- Find the position for the first reference point at one of the corner pillars and glue the precision washers at the point as high up as possible for maximum visibility.
- The next reference points must be fixed such that they are well spread out and cover as much area as possible.
- After all the reference points are chosen and the precision washers are fixed, these points are surveyed using a total station and prisms with same center point as the reference spheres used while scanning.

Things to remember:

- Don’t place two nearby reference points in the same height
- Don’t follow any strict patterns while choosing the reference points
- Don’t choose the reference points against reflective/white surfaces
- For smooth registration of the scans, there needs to be at least 3 common targets in two consecutive scans. This depends on the scan positions and the spread of targets.
2. Survey:

Surveying of reference points requires a total station and a skilled surveyor. The resulting survey data must be in .txt, .csv or .cor file format in order to use it during the processing of scans.
Scanning

This chapter describes how to plan the scan positions and the settings to be chosen on the scanner before starting to scan.

1. Set up the equipment

   The equipment includes the scanner, SD cards, battery, charging adapter and a tripod. Set up the tripod and mount the scanner onto the tripod. Check if the scanner is fastened tightly to the tripod.

2. Plan the scan positions

   - The number of scan positions depends on the number of objects present in the scan environment and the required level of detail of the objects. For example, if a machine in the environment is not important to be scanned from different angles (example, if the back of the machine is unimportant), we can reduce a scan position.
   - Fix the available reference spheres at the precision washers.
   - Start by choosing the first scanner position at one of the corners of the facility, with as many reference spheres as possible in sight of the scanner (minimum three).
   - The scan position should be such that the spheres form a polygon around the scanner.
   - The second scan position must be such that it has at least 3 common targets with the first scan. The more spheres in the first scan position, the easier it becomes to choose the second scan position.
   - For the rest of the scan positions, follow a trail making sure to cover at least three spheres from the previous scan every time.
   - Mark your scan positions with a temporary marker like a normal tape.
   - Retrace the trail and ensure each scan position covers at least three reference spheres from its previous scan position.
3. Choose the required settings

There are two types of settings that needs to be addressed before the scanning is started:

**Manage**

This includes general device settings such as language, date format, date and time and so on. The user interface is similar to that of a smartphone. This menu also allows the user to name the scan project.

**Parameters**

This includes settings related to the scan and the following are some of the most important parameters to be considered:

- Profiles: Pre-set profiles based on the environment being scanned
- Resolution: number of points (point density);
  - Quality: number of times each point is scanned
  - Scan duration depends on these and can be seen on the screen as you select these parameters. Also, on the screen you can see the point density (distance between points) and number of times a point gets scanned.
- Scan range: Horizontal and vertical ranges or coverages of the scan
- Sensors: Keep all the sensors “on” except GPS. When the sensors are switched on (Inclinometer, Altimeter, Compass) the data recorded by them will be automatically used during registration in Faro Scene.
- Colour settings: Exposure settings for the photos.

The major parameter settings and their suggested values to keep in mind before starting the scan is shown in the following table. These are the settings suggested for scanning most factory environments. Make sure to consider the exceptions if they apply.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Suggested</th>
<th>Exceptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profiles</td>
<td>Indoor ..10m</td>
<td>If objects of interest are too far from scanner, choose Indoor 10m.</td>
</tr>
<tr>
<td>Resolution</td>
<td>¼</td>
<td>If there are lack of targets and they are far from the scanner, choose higher resolution</td>
</tr>
<tr>
<td>Quality</td>
<td>2x-3x</td>
<td>N/A</td>
</tr>
<tr>
<td>Scan range</td>
<td>Default</td>
<td>If you do not need details such as pipelines on the ceiling reduce the vertical range</td>
</tr>
<tr>
<td>Sensors</td>
<td>Keep everything ON other than GPS</td>
<td>N/A</td>
</tr>
<tr>
<td>Colour settings</td>
<td>Even weighted Metering</td>
<td>In case of low lighting, use horizon weighted metering to capture maximum light possible</td>
</tr>
</tbody>
</table>

**Important!**

- Calibrate the inclinometer so it is levelled to zero. (Home > Manage > Sensors > Inclinometer)
- When scanning a confined space reduce the resolution since it will result in a dense point cloud anyway.
- Make sure to turn on the option “Scan with Colour” under the parameters menu if you need colorized scans.

4. Start the scanning process

Press the “Start Scan” button on the home screen and leave the scan area as soon as possible. Make sure that there are no movements (human or machine) while the scanning is being carried out. During scanning the scanner blinks with a red light and while taking pictures, it blinks blue light. When the process is complete a stable blue light stays on the scanner. Then, move the scanner to the next scan position and carry on the scanning.
Scan Data Management

The process chapter explains a step by step procedure to be followed to process the scan data on Faro Scene and various that can be used to manipulate and edit the scans.

1. Open Faro Scene

The processing of the scans can be done in Faro Scene v7.1, which is available for download from FARO website. The trial version has a 30 days validity. If the 3D scanner is to be used regularly then it is preferable to use the licensed version of the software.

2. Create project

For a new project, click on ‘Create Project’ and enter the file name. A new project window will appear. Click on the ‘Import’ tab and import the ‘.fls’ folders into Faro Scene.

3. Process the scans

The next step is called ‘Processing’. In this step, the user can choose the option to colorize the scans, create point clouds, etc. In order to colorize the scans, the color option has to be selected from the scanner menu before starting the scan. Also, the user should make sure to select the “Colorize Scans” option from the General setting, which significantly increases the processing time, if the point cloud is intended to be coloured or else the point cloud would be in grey scale.

Distance filter is another feature where one could choose the maximum distance for capturing the point cloud.

Select the appropriate target type from the given list under “Find targets”. In case of spheres, choose the correct radius of the spheres used, i.e. 0.07m for size M or 0.1 m for size L.
Configure the settings for processing. The default values for this page can be changed in the settings.

Selected Scans: 2

- General
  - Colorize Scans
  - Create Scan Point Clouds
  - Skip Fully Processed Scans

- Filters
  - Dark Scan Point Filter
    - Settings
  - Distance Filter
    - Settings
  - Stray Point Filter
    - Settings
  - Edge Artifact Filter

- Find Targets
  - Find Checkerboards
  - Find Markers
  - Find Planes
  - Find Spheres

Active Sphere Radii: 0.0700 m, 0.1000 m

Figure 17: ‘Processing’ window with the required settings
4. Import surveyed points

The reference points measured during the initial planning is imported into Faro Scene at this step by clicking on the option marked in figure 18. From this option, import the .csv survey data file into cluster level. Faro Scene will add these points under “References” folder in the structure tree.

Figure 18 Top: Survey points import option before registration; Bottom: Example .csv file of survey data

In figure 18 (bottom), A100 is the name given to the reference point whose x, y and z coordinates are 229.1098, 100.1224 and 2.9274 respectively. Make sure this is the format followed for importing the survey data.
5. Register the scans

3D scanning has to be performed from different positions. It helps the scanner to capture an object from every possible angle. Therefore, every scan has its own coordinate system with its origin being the position from where the scanning was performed. In the registration process, the scans are stitched together and the transformation from local coordinate system to global coordinate system is made.

The user can create clusters in the registration window (Figure 18) which is a collection of similar scans together. This is usually done to categorize scans for different floors or rooms.

If targets are used during scanning, use target-based method for registration. During the registration process the user can opt for finding the targets automatically which can be verified later. If FARO Scene is not able to find the targets then user can select the targets manually as shown in figure 20. Objects that could be used as targets are spheres, checkerboards, etc. In most of the cases, spheres are preferred because of its visibility from various angles.

It is important to select “Find correspondence for scan positions” to place the scans according to the surveyed points.
When the registration is over, Faro Scene will ask for point cloud verification in two steps. Figure 20 shows step 1, where the user can verify if all targets are recognized by the software. In step 2 (Figure 21), the user can check if the scans are placed correctly. If there are unnecessary points outside the area of interest, it is a must to add a clipping box in this step to delete points outside of the box in the later stage.
6. Editing point cloud (Explore Tab)

The user has the opportunity to edit the point cloud after the registration process. The user can select one of the scans from the left tab and can have the 3D view from that scan position. Figure 22 shows the different tools available to use to edit the point cloud. Figure 23 is an example of how the Explore window looks like.

Some of the features to explore in Faro Scene:

- **Annotation**: The annotation feature helps in adding description to an object in the scan area. It could include position or textual description.
- **Selecting the points in cloud**: This could be done either by selecting the polygon or brush tool. By doing so the points could be deleted. One should remember that this process is irreversible in Faro Scene.
- **Clipping box**: Clipping boxes help to sliver the areas of the point cloud that are not required.
- **Supersampling**: It makes the appearance of the point cloud smoother by increasing the resolution and fitting it in the screen. But for supersampling to work smoothly one needs to have good hardware specifications.
7. Project Point Cloud:

The changes made to the point cloud have to be saved. This can be done by selecting Project Point Cloud from the toolbar. The dialog box in figure 24 shows some additional filters to apply to the point cloud.

- Eliminate duplicate points: Removes duplicate points.
- Close surfaces: Combines the points on a recognized surface and visualizes it in a solid form.
- Homogenize Point density: Results in a more uniform point density across the point cloud.

![Image of Project Point Cloud / Scan Point Cloud Settings dialog box]

*Figure 24 Create point cloud window*
1. Transform the point cloud

To be able to visualize the point cloud in CAD software such as LayCAD or NavisWorks, it is important to transform the coordinate system of the point cloud to that of the building coordinate system (which is the base for the 2D layout drawings on LayCAD). This involves translating the coordinates of the point and rotating it to match the orientation of the building coordinate system, which is explained in this step.

a. Orientation of point cloud:

The scans placed after the registration process are normally not oriented in a defined manner. But, in order to be able to visualize the point cloud over the 2D layout in a CAD software (LayCAD/NavisWorks), it is important to match the point cloud’s orientation to the building drawing’s orientation. To do this, simply follow these steps,

• Locate a wall, ceiling or any straight surface in the point cloud.
• Assign a plane to this surface.
• Repeat the same for one or two more surfaces.
• In the structure tree, right click on the plane you just created and choose alignment.
• Here, you have the option to select the direction the plane needs to be aligned to (North, South, East, West, Ceiling, Floor, Custom). Select the appropriate alignment for all the planes.
• To confirm the alignment change the views of the point cloud (top, isometric, etc) to check if the point cloud’s orientation has changed.
• After this is done, delete the selected planes.

Note: Orientation steps can be skipped if the coordinate system is oriented according to building coordinate system during surveying of reference points (Mention the correct orientation to the surveyor)

b. Reference point selection:

• Choose a point in the scans which can be easily selected in the layout drawing (ex: Corner of the room, corner point of a pillar, etc).
From the drawing of the layout in LayCAD, select the same point selected on the point cloud and extract its coordinates \((p_x, p_y, p_z)\)

c. Calculation of offsets:

> Note: To check the coordinates of “Scans” (Figure 25) or a point, right click on the element on the structure tree (Figure 25) and select Properties > Transformation tab

Let,

- a. Point cloud point – \((P_x, P_y, P_z)\)
- b. Drawing point - \((p_x, p_y, p_z)\)
- c. Scans (Figure 25) – \((S_x, S_y, S_z)\)

The goal is to calculate offsets of a in relation to b. This is done through the following steps:

- To calculate the new reference scan coordinates

\[
[(p_x - P_x), (p_y - P_y), 0] = (N_{sx}, N_{sy}, 0)
\]

- To calculate the new Scans coordinates

\[
[(N_{sx} + S_x), (N_{sy} + S_y), 0] = (N_S x, N_S y, 0)
\]

By entering the values of \((N_{Sx}, N_{Sy}, 0)\) in the “Scans” (Figure 25) transformation properties in the structure tree, the scans will successfully be translated to the required coordinate system. But before that, the z axis values, which is the height of the “Scans” needs to be calculated, which is done as follows:

- Mark a point on the floor (or where you want the zero point of the z axis to be) next to the reference scan position
- Choose “Measure between objects” and measure the distance between the point and the scanner.
- The vertical height gives the z axis value to be entered in the “Scans” (Figure 25), i.e, \(N_S z\).
d. Scan Transformation

![Figure 25 "Scans" folder on the structure tree](image)

Enter the coordinates (NSx, NSy, NSz) in the “Scans” transformation properties (Figure 25) in the structure tree and the scans are now successfully translated to the required coordinate system.

2. Export project point cloud to `.e57`.

After exporting the point cloud in `.e57` format, import this file in Autodesk ReCap and save the project in `.rcp` format. The `.rcp` file can then be attached as external reference on AutoCAD or NavisWorks to visualize against 2D CAD Drawing.
Scan Update

This chapter explains the procedure to be followed in order to replace an existing point cloud with new and updated scans.

One of the advantages of having surveyed reference points is that it allows us to place the point cloud in a known coordinate system. As a result, any new scans performed in the same facility can be referred to the same known coordinate system by importing the survey data into Faro Scene.

This means that when scanning the same area again, there is no need to plan the reference sphere positions and also transformation of the point cloud becomes unnecessary.

New scans can be carried out and updated through following steps:

1. Plan the new scan positions:
   - When there is a change in the facility that needs to be recorded, pick approximately the same scan position chosen initially around the area to be updated.
   - Scan the area to be updated form as many scan positions as possible.
   - The more the scan positions and the closer the new scan positions are to the initial ones, the better the quality of the point cloud.
   - Follow the same procedure as in the “Scanning” chapter.

2. Process the new scans:
   - Delete the scans that have to be replaced from a point cloud which has survey points imported.
   - Import the new scans with the changes.
   - Process the new scans.
   - Register the scans. Make sure that "Find correspondences for scan positions" is selected.
     The new scans will now be placed in the previous referenced coordinate system.

   N.B.: To maintain the quality of the point cloud, replace as many scans as possible when there is an update to be made

As seen here, the updating of existing scans is a shorter process than the initial scanning procedure. With the survey data, it is always possible to refer your new scans to the previous point clouds’ coordinate system which eliminates the need to transform the scans every time.
Things to remember while scanning:

➢ One should be wary of capturing glassy or mirrored surfaces
➢ The distance of the surrounding objects to the scanner should be taken into account
➢ The targets should have a contrasting background or it could be a problem while registering the scans
➢ The laser from the scanner should be able to reach the targets. It is important while creating point cloud
➢ Suitable quality and resolution should be selected depending on the surrounding
➢ It is advisable to plan the placement of the scanner beforehand
➢ Range of the scanner varies depending on the model
➢ Choose appropriate settings from the menu
➢ Avoid movement during scanning
➢ Try to cover as much area as possible in order to get a good point cloud
➢ It is important to have good lighting if coloured scans are needed
➢ Avoid placing the targets in the shadow