LESSONS LEARNED FROM 3D LASER SCANNING OF PRODUCTION SYSTEMS

Erik Lindskog[1], Jonatan Berglund[1], Björn Johansson[1], and Johan Vallhagen[2]

[1] *Chalmers University of Technology, Product and Production Development, 41296 Göteborg, Sweden*
[2] *GKN Aerospace Engine Systems, Production Research/System, 46181 Trollhättan, Sweden*

erik.lindskog@chalmers.se

Abstract: 3D laser scanning is a technology that can be used for creating accurate and realistic virtual representations of production systems. The purpose with this paper is to present lessons learned from how to carrying out the 3D laser scanning. These lessons learned derive from a review of six industrial studies that applied 3D laser scanning to solve different production related problems. The review shows that good planning and preparation is key factors for high quality and accuracy of the resulting scan data.

Keywords: 3D laser scanning, Point cloud, Production systems, Virtual production, and Visualisation.

1. INTRODUCTION

Manufacturing companies are often required to adjust their production systems to face factors such as sales volumes, product changes, or other strategic improvements. Such adjustments may require the production systems to be redesigned, which can comprise of minor changes in a workstation or installation of new machines and other equipment. These redesign tasks often require rigorous planning, which is usually supported by the use of virtual manufacturing tools. Such tools are for example applications for layout planning, simulation of production flows, or ergonomic evaluations (Schuh, *et al.*, 2011). These applications often require a virtual representation of the production system, which traditionally are modelled in 2D or 3D CAD. However, the problem is that most often these representations are not modelled in such way that they are accurate and realistic virtual copies of the real production systems (Gregor, *et al.*, 2009). To address this problem there is a possibility to use 3D laser scanning for capturing spatial data of the production systems to be used for creating the virtual representations.

The 3D laser scanning technology has been developed during the last decades for a number of applications and business areas, such as heritage documentation, forensics, and tunnel mapping (Bi and Wang, 2010; Sansoni, *et al.*, 2009). The technology has the capability to capture spatial data with high accuracy of large physical environments as well as smaller objects. The spatial data is usually used for creating virtual representations of the captured environment or object. These virtual representations are based on hundreds of millions measurement points combined in accurate and realistic point clouds. It has been shown that the point clouds of factory environments are promising for a number of applications when redesigning production systems. By making modifications to the point clouds or adding additional 3D CAD models it is possible to visualise future changes to the production system (Lindskog, *et al.*, 2013). Point clouds have also been used to represent sections of existing production systems in for example discrete event simulation models, which increase the level of visualisation in the simulation model (Lindskog, *et al.*, 2014). Volvo Cars Corporation uses, for example, point clouds as the main virtual representation of their factories' layouts, which enable them to ensure accurate planning when redesigning their production systems (Alpman, 2013).

The possibility of using 3D laser scanning to create virtual representations of production systems has been applied in research during the last decade. Publications from this research has mainly focus on presenting how to use and apply the scan data with minor focus on the actual 3D laser scanning process. The purpose with this paper is to present lessons learned from how to carry out the 3D laser scanning process. These lessons learned derive from a review of six industrial studies from the last three years where 3D laser scanning has been applied to solve a number of production related problems. The review is based on the purpose with the scanning, specific conditions, experiences, and resulting scan data from each study.

The paper is organised in four additional sections. In the next section, 3D laser scanning theory is presented. This section is followed by a description of the industrial studies in section 3. The lessons learned from the review of these industrial studies are summarised in section 4. Finally, the paper is concluded in section 5.

2. 3D LASER SCANNING

3D laser scanners operate by emitting laser beams and capturing their returned reflection to measure the travelled distance (Klein, *et al.*, 2012). Each captured reflection represents a sample of the surface of the closest object along the measurement direction, which is referred to as a measurement point (Klein, *et al.*, 2012). The measurement points store information about the position in x, y, z coordinates and the intensity (Staiger, 2003). The type of 3D laser scanner addressed in this paper belongs to the group panoramic terrestrial laser scanners mounted at tripods (Staiger, 2003). These scanners have a typical field of view in the horizontal axis of 360 degrees and in the vertical axis of 300 to 320 degrees, which is exemplified in Fig. 1 (Dassot, *et al.*, 2011). By systematically capturing measurement points in the field of view, the scanner generates a complete geometrical representation of the environment. This systematic capturing is referred to as a scan in which the scanners have the capability to gather tens of millions of measurement points during a few minutes (FARO Technologies, 2013; Klein, *et al.*, 2012). For enhanced visualisation each measurement point can be complemented with information about the colour based on the RGB colour model, which is generated from photos taken by a built-in camera during each scan (FARO Technologies, 2013). The process of creating a representation of a complete environment, most often requires scans from a number of locations. To make it possible to combine two scans into one dataset, at least three corresponding reference objects need to be visible in both scans to combine them successfully (FARO Technologies, 2013). The reference objects can for example be white spheres or black and white checkerboards, as presented in Fig. 2.

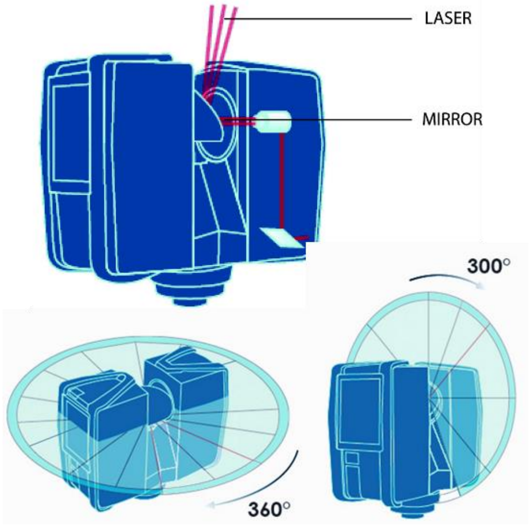

Fig. 1. 3D laser scanning capturing (FARO Technologies, 2013).

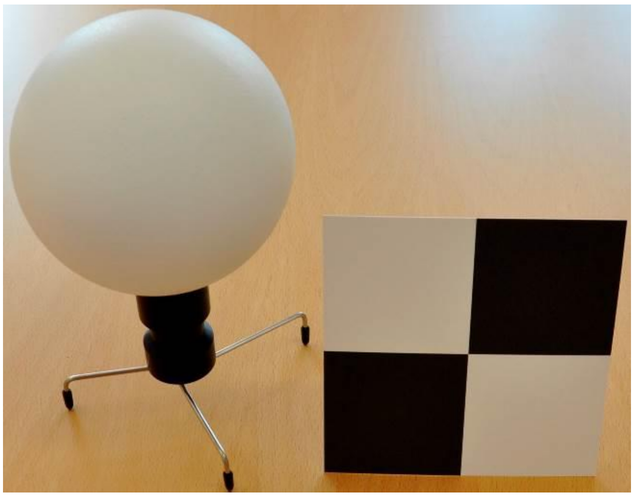

Fig. 2. A spherical reference object (left) and a checkerboard reference object (right).

The scanning process can be divided into three steps, as follow (FARO Technologies, 2013):

1. *Prepare scanning* - The locations of the scanner and reference objects are planned to ensure that all necessary data can be captured. It is important to consider the line of sight from the scanner to the objects of interest as well as the line of sight to the reference objects. To capture a production facility with its many interior objects such as machines and material facades it is necessary to scan from several locations.

2. *Perform scanning* - Locate the scanner at the planned locations and execute the data capture. For good results, it is important that the environment remains motionless throughout the scanning process. With the 3D laser scanner referred to in this paper, a typical setting for an indoor scanning will result in 20-40 million measurement points in RGB colour in five to seven minutes per scan.
3. *Process scan data* - The data from all scans are aligned and combined into one dataset in a semi-automated registration process. This alignment is made using the reference objects or other specific building objects.

The above process results in a dataset representing the scanned environment. The size of the dataset depends on the set scanner resolution and number of scans, and can vary between a few thousands to billons of individual measurement points (FARO Technologies, 2013). This dataset can be used to generate a point cloud, which consisting of all the individual measurement points. The resulting point cloud can be made sparser by filtering away a percentage of the measurement points (FARO Technologies, 2013). This reduces data size and can be done to various degrees depending on the target application and processing performance. The point cloud can also be cleaned from any unwanted measurement points. Examples of unwanted measurement points are sensor noise and partially captured moving objects. Typical additional operations performed on point clouds are objected based selection and bounding of a subset of measurement points. Such selection can for example be used to separate a robot from the overall point cloud and save it as a stand-alone point cloud, as exemplified in Fig. 3.

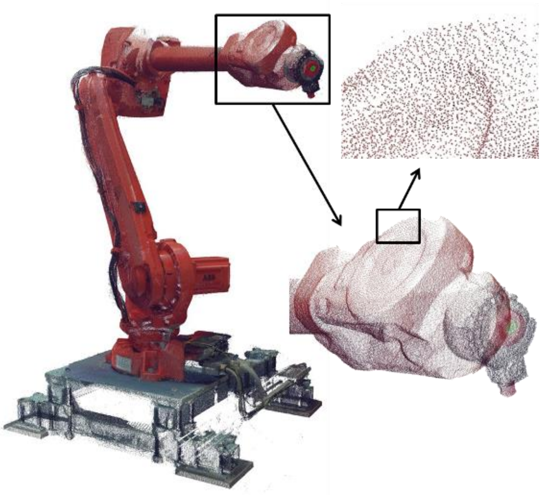

Fig. 3. Point cloud representing a robot and a close-in of the surface.

There are several approaches available of how to visualise the resulting scan data. Two commonly used approaches are to visualise panoramic views of individual scans or the entire datasets as point clouds. Panoramic views of individual scans can be described as looking at spherical 360 degrees photos, which can be compared with how Google street view works. By virtually assuming actual scan locations, it is possible to make measurements and study the scanned environment in detail. Panoramic views can be provided in standalone desktop applications or web-based applications. Such an example of a web-based application is FARO SCENE WebShare, presented in Fig. 4, which also provides an overview map to visualise the layout of the scanned environment in 2D (FARO Technologies, 2014). The approach of visualising the scan data as point clouds enables the possibility to move freely through the scanned environment in 3D and analyse the scan data in close detail. An example of a desktop application visualising point clouds is FARO SCENE, which is exemplified in Fig. 5 (FARO Technologies, 2014). The point cloud approach makes it possible to visualise and evaluate changes in the scanned environment by translating subsets of the point cloud or by adding CAD models.

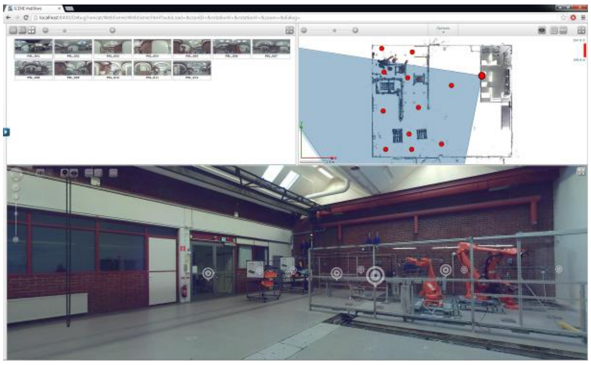

Fig. 4. Panoramic view from one scan location in FARO SCENE WebShare.

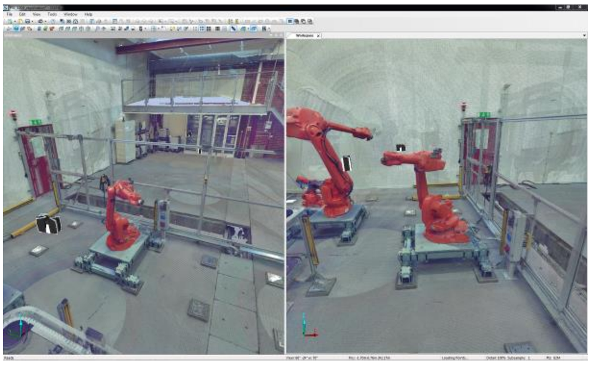

Fig. 5. Two views of a point cloud in FARO SCENE.

3. DESCRIPTION OF INDUSTRIAL STUDIES

The six industrial studies were carried out between 2011 and 2014 at manufacturing companies in Sweden and Norway. In each industrial study, entire or sections of the company's production system was 3D laser scanned. Theses production systems were mostly similar, mainly product oriented with standalone machines or production units. As presented in Table 1, the purpose of the each scanning was slightly different between the studies. The scanning purposes mainly derive from how the resulting scan data should be used.

The 3D laser scanner used in the six industrial studies was a FARO Focus 3D 120 phase shift laser scanner set to capture colours, a resolution of 1/5, and to the different speed settings according to Table 1. These settings resulted in a maximum of 28.8 million measurement points for each scan. The time for each scan was approximately 5 minutes using the speed 244 kilo points per second (kpt/s) and approximately 7 minutes using the speed 122 kpt/s. The reference objects used were primary 139 millimetres white spheres and, in some of the studies, 150 x 150 millimetres black and white checkerboards. The number of available spheres was 8 and checkerboard was approximately 30. Tripods and other fastening devices were used to attach the reference objects to physical objects in the production systems. To provide the possibility to align future scans with the previous ones of the same production system, fastener plates for the spheres can be mounted permanently in the factory. Such plates were mounted during *Industrial study A* at different locations in the building. These plates were then reused when a section of the same building was scanned in *Industrial study C*.

The time for preparing each scanning was around one hour, which was mainly spent on deciding the positions of the scanner and reference objects. The actual scanning time for each study, from starting the first scan to finalising the last one, is presented in Table 1. Processing the resulting scan data was made during approximately one workday in each study. A majority of the scans were carried out during work hours with people working in the production system. To not disturb the scanning, people were temporary prevented to be inside or enter the scan area during each scan. The possible to prevent people to enter, required a scanning team of 2-5 persons for each scanning. However, in *Industrial study A* it was not possible to prevent all people entering the scan area due to a large amount of construction personnel working in the building.

Table 1. Summary of the industrial studies.

Industrial study	**Scan purpose**	**Scan area**	**Number of scans**	**Scanning time**	**Speed**	**During work hours**
A	Capturing an almost empty factory with focus on building specific information.	3500 m^2	13 scans	3 hours	244 kpt/s	Yes
B	Capturing a production system with focus on detailed information of the machines and surrounding equipment.	1500 m^2	22 scans	4 hours	244 kpt/s	Yes
C	Capturing an in-bounded robotic cell and the surrounding environment with high level of detail.	800 m^2	13 scans	2.5 hours	122 kpt/s	Yes
D	Capturing a production system in general.	1900 m^2	23 scans	3.5 hours	244 kpt/s	No
E	Capturing a production system with focus on building specific information.	1700 m^2	12 scans	2 hours	122 kpt/s	No
F	Capturing a robotic cell and the surrounding environment.	400 m^2	8 scans	1 hours	122 kpt/s	Yes

4. LESSONS LEARNED

The review of the six industrial studies resulted in a number of lessons learned of how to ensure good quality of the result from a 3D laser scanning. These lessons learned cover the entire scanning process, from before entering the factory to processing and deliver the resulting scan data. Before starting the actual scanning process in the factory, it is required to plan how to carry out the process. As presented in Table 1, each industrial study had a different purpose with the scanning, which affected how the scanning was carried out. It was learned that it is important to establish the purpose of the scanning during the planning, to ensure that the right focus is kept during the scanning. The purpose has shown to be important for how the different steps of the scanning process can be carried out and to guide on-site decisions. Additionally, during the planning, it is important to identify how the scan data will be used and what level of detail that is required.

Ideally, the scanning process is carried out when there is no ongoing production or personnel in the factory. However, this is not always possible due to a number of reasons and not always necessary. As stated in the description of the industrial studies, most of them were carried out during full production and with personnel in the factory. When scanning during full production it has been shown to be important to inform the shop floor personnel about the scanning and that it might require interruptions or stops affecting parts of the production. Fewer disturbances during the scanning will reduce the scan time and increase the quality of the resulting scan data.

4.1. Prepare scanning

Preparing the scanning process in the factory has shown to be an important prerequisite for achieving good quality and accuracy of the resulting scan data. During the preparation, the scanner operator should have the scanning purpose in mind to ensure right focus. The main task during the preparation is to plan the locations of the scanner and the reference objects. The scanner locations derive from factors such as the scanning purpose, the factory layout, and the level of detail to capture. As presented in Table 1, the relation between the scan area and number of scans are not consistent. For example, *Industrial study A* with the purpose to scan a more or less empty factory building made it possible to have rather longer distances between the scanner locations. However, when scanning a section of the same factory in *Industrial study C*, the purpose was to capture detailed information of a newly installed in-bounded robotic cell. In this study, several scans within close range of the cell were required. Another example is *Industrial study F*, where the purpose was to capture as much detail as possible of the robotic cell requiring several scans in a close range. At each scanner location, the scan should cover as much data as possible that is not already covered by other scans. Reducing the overlap between different scans will make it possible to scan a larger area in less time. However, several scans in close range might still be needed to cover all angles of for example a machine.

The distance between the scanner and the object of interest should be considered when deciding the scanner locations. Locating the scanner too far away from the object will reduce the number of measurement points captured on the object of interest. However, if the scanner is located too close to the object this can result in that data are missed due to that the scanner only covers around 300 degrees on the vertical axis resulting in lack of scan data below the scanner as in Fig. 6. Similar problems can occur when there are objects blocking the view from the scanner, as exemplified in Fig. 7. The problem in this example is that there will be lack of scan data shaped as the objects. This lack of data can most often be solved using data from other scans covering that same area, however, the shape of the objects might still be visible due to fewer measurement points or colour variations.

Fig. 6. The gap of scan data below the scanner.

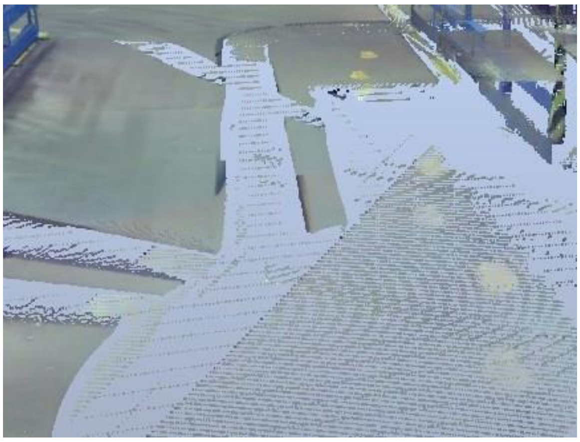

Fig. 7. Problem with insufficient amount of scan data.

A problem identified in the industrial studies is the difficulty to get scan data of the top of machines and other equipment, which can be important when studying a 2D or top view of the scan area. In *Industrial study C*, this problem was addressed by locating the scanner on the top of the in-bounded robotic cell in one of the scans and in *Industrial study E*, by locating the scanner on a staircase to the second floor. Such alternatives might not always be possible and the purpose of the scanning should determine if it is motivated.

When the locations of the scanner have been decided, reference objects need to be located in the scan area in such way that the scanner can identify them and that they are not moved during or between different scans. The possibility to identify a reference object depends on the set resolution, size of the object, distance, and angle to the object. As stated in the description of the industrial studies, the primary used reference objects were spheres. For the size of the spheres and the resolution used in the industrial studies, the maximum allowed distance between the scanner and a sphere was approximately 15 metres. If using other sensors, such as the built in inclinometer as a reference for the x-y plane, it will be possible to use only two corresponding reference objects. However, a lesson learned is to use three or more corresponding spheres due to the risk of problems with identifying some spheres. It is also recommended to use checkerboards as a complement and backup to the spheres.

4.2. Perform scanning

With good preparations, the actual scanning should be a straightforward process. Before starting each scan, the operator needs to ensure that the scanner will identify enough reference objects. If there is a lack of identified reference objects, either the location of the scanner can be adjusted or additional reference objects can be added to the scan area. When the reference objects are verified, the scanner operator needs to ensure that there are no persons inside the scan area. After pressing the start button, it is important that the scan area remains static until the scan is finalised. People crossing the laser beam will create problems in the resulting scan data, as exemplified in in Fig. 8 where the persons crossing the laser beam created holes in the wall behind them. Another example is Fig. 9, where a person entered the scan area during the colour capturing resulting in a miscolouring of the wall. For the best result, the scan area should remain static during the entire scan. To stop people from entering the scan area, most industrial studies has require several people to watch the entire scanning perimeter.

Fig. 8. Persons crossing the laser beam during a scan.

Fig. 9. Persons standing inside the scan area during only the colour capturing.

The main problem identified with scanning during full production, in addition to people crossing the laser beam, is to ensure that the entire scan area remains the same throughout all scans. Objects that are moved between different scans will cause problems in the resulting scan data. An example of such a scenario was in *Industrial study B*, as presented in Fig. 10, where a container was moved between different scans. The moving of the container resulted in that the container is only partly visible in the resulting scan data. Other problems identified when scanning blank surfaces and lattices with small radius, as exemplified in Fig. 11. These geometries usually result in some type of quality problems in the scan data and, if possible, they should be avoided.

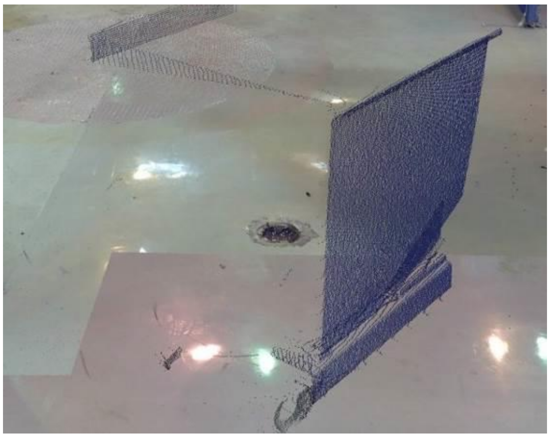

Fig. 10. Problem with moving objects.

Fig. 11. Quality problems with scanning a lattice.

After each scan, the scanner operator might need to move some of the spheres to use them in other scans due to a limited amount of spheres available. However, it is important to ensure that previous locations of the spheres should not be used again in upcoming scans before moving them. Only if using mounted fastener plates as in *Industrial study A* and *C*, it is possible to ensure the same location of the spheres again if they have been moved.

4.3. Process scan data

The scan data that is captured in the factory needs to be processed before it can be used. This process is most often automated by using scanner vendor specific applications. It is also possible to use applications that accept scan data from different vendors, such as Autodesk Recap. In the industrial studies, FARO SCENE was used to process the scan data. The process involves steps such as combining the different scans, filtering the scan data, and applying colours. How well the scans are combined is related to whether or not the application identifies the reference objects properly. The application mostly identifies the reference objects automatically, but in some scans it might be needed to identify them manually. It is also possible to manually define other geometries as references, such as a plane from the surface of a wall that is visible in more than one scan. When all scans are combined successfully, the scan data can be filtered using different parameters to remove unwanted measurement points. For example, removing measurement points that are a result from the quality problem created by scanning lattices as described above. The final scan data can then be colourized using the pictures captured by the scanner during each scan.

After processing the scan data, it can be exported in different file formats depending on how the data should be used. Example of exports applied in the industrial studies were either to FARO SCENE WebShare format or as point clouds in different formats to be used in other applications. The WebShare format has shown to be suitable sharing the scan data to a large number of users that should have the possibility to make measurements and navigating in the scanned facility. Point clouds can be used for a number of applications, and the general accepted file format E57 was identified as most suitable for most applications (ASTM, 2011). The point cloud can be modified to visualise different future scenarios of the scanned production system. However, a problem identified with making modifications to the point cloud is that holes may occurs in the point cloud, for example if moving a machine this will result in a hole in the floor or in the wall behind.

5. CONCLUSIONS

The review of the six industrial studies has shown that there are a number of factors that needs to be considered before and during 3D laser scanning of production systems. Before starting the scanning process, a clear purpose should be established. This purpose should cover factors such as how the resulting data will be used, what resolution and level of detail that are required, and if there is some section of the scan area that are more important than others. A clear purpose will support the preparations in the factory, and good preparations have shown to be important for how to carry out other phases of the scanning process as well as increase the quality of the resulting scan data. With a good result from the scanning process, the scan data has a high potential to support production engineers to solve a number of problems when redesign production systems.

ACKNOWLEDGEMENT

This work is funded by VINNOVA (Swedish Agency for Innovation Systems), and the NFFP6 program. This work has been carried out within the Sustainable Production Initiative and the Production Area of Advance at Chalmers University of Technology. The support is gratefully acknowledged.

REFERENCES

Alpman, M. (2013). Nya modeller testas direkt i laserskannad kopia av fabriken. NyTeknik. http://www.nyteknik.se/nyheter/automation/cad/article3641535.ece (accessed 2014-04-02).

ASTM (2011). Standard Specification for 3D Imaging Data Exchange.

Bi, Z.M. and Wang, L. (2010). Advances in 3D data acquisition and processing for industrial applications. *Robotics and Computer-Integrated Manufacturing*, **26**, 403-413.

Dassot, M., Constant, T. and Fournier, M. (2011). The use of terrestrial LiDAR technology in forest science: application fields, benefits and challenges. *Annals of Forest Science*, **68**, 959-974.

FARO Technologies (2013). FARO Laser Scanner Focus3D Manual.

FARO Technologies (2014). FARO SCENE 5.2 Manual.

Gregor, M., Medvecký, Š., Matuszek, J. and Štefánik, A. (2009). Digital Factory. Journal of Automation, *Mobile Robotics & Intelligents Systems*, **3**, 123-132.

Klein, L., Li, N. and Becerik-Gerber, B. (2012). Imaged-based verification of as-built documentation of operational buildings. *Automation in Construction*, **21**, 161-171.

Lindskog, E., Berglund, J., Vallhagen, J. and Johansson, B. (2013). Visualization support for virtual redesign of manufacturing systems. In: *Forty Sixth CIRP Conference on Manufacturing Systems 2013*, 419-424.

Lindskog, E., Berglund, J., Vallhagen, J. and Johansson, B. (2014). Lean Based Problem Solving using 3D Laser Scanned Visualizations of Production Systems. *International Journal of Engineering Science and Innovative Technology*, **3**, 556-565.

Sansoni, G., Trebeschi, M. and Docchio, F. (2009). State-of-The-Art and Applications of 3D Imaging Sensors in Industry, Cultural Heritage, Medicine, and Criminal Investigation. *Sensors*, **9**, 568-601.

Schuh, G., Aghassi, S., Orilski, S., Schubert, J., Bambach, M., Freudenberg, R., Hinke, C. and Schiffer, M. (2011). Technology roadmapping for the production in high-wage countries. *Production Engineering*, **5**, 463-473.

Staiger, R. (2003). Terrestrial laser scanning technology, systems and applications. In: *2nd FIG Regional Conference*.