Proceedings of the 2014 Winter Simulation Conference
A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, eds.

USING 3D LASER SCANNING TO SUPPORT DISCRETE EVENT SIMULATION OF PRODUCTION SYSTEMS: LESSONS LEARNED

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ABSTRACT

Using 3D laser scanning, the spatial data of an entire production system can be captured and digitalized in a matter of hours. Such spatial data could provide a current state representation of the real system available at the hand of the simulation engineer. The purpose of this paper is to evaluate the use of 3D laser scanning in Discrete Event Simulation (DES) projects in the area of production systems. The evaluation relies on three simulation studies performed with the support of 3D laser scanning. 3D scan data, if available, can support most steps in a DES study. Particularly, the 3D scan data acts as a reference model when formulating the conceptual model and collecting input data. During model building the scan data provides physical measurements for accurate positioning of simulation objects. Furthermore the scan data can be used for photorealistic visualization of the simulated environment without requiring any CAD modeling.

1 INTRODUCTION

3D laser scanning is a technology for capturing spatial data in three dimensions. The technology originates from the field of surveying and has since been spread to several other application areas. The common denominator for the technology's application across different fields is the ability to capture spatial attributes of the real world and make them available for analysis and visualization in virtual environments. In fields such as transportation, archeology, and crime scene investigation, 3D laser scanning has been successfully integrated to support and develop the traditional work flow (Jaselskis, Zhili and Walters 2005; Lerma et al. 2010; Sansoni, Trebeschi and Docchio 2009). Applications of 3D laser scanning in the field of production include, but is not limited to, planning and validation of equipment installations, offline factory layout planning, and robot programming or material movement paths (Lindskog et al. 2013; Tafuri et al. 2012; Berglund et al. 2013).

Discrete Event Simulation (DES) engineers involved in production development projects, often are not subject matter experts on the specific production system to be modeled. Therefore, the success of such projects rely on subject matter experts to provide data and descriptions of the functionality of the production system. The subject matter experts can be e.g. production engineers, operators, or production planners. For a simulation study to have a chance of being successful, all involved parties should have a well enough aligned mental model of how the system to be modeled functions. Since a mental model is internal to its holder, it cannot easily be aligned and miscommunication is listed as the most common reason for unsuccessful simulation studies (Musselman 1994). Studies have shown that 3D scan data can support the DES experts with accurate and comprehensive spatial data of the production system at hand (Jansson and Roos 2013; Lindskog et al. 2012; Berglund et al. 2013).

The purpose of this paper is to present lessons learned from integrating 3D laser scanning in simulation studies. In an attempt to concretize experiences to date from such integration, three previously conducted DES projects have been reviewed. To date there are a limited number of studies combining 3D laser scanning and DES available, and few academic publications describing them. Hence, the reviewed studies have all been carried out with the involvement of one or more of the authors of this paper. The basis for the review of the three studies is a combination of published reports, papers, and, inescapably, the authors' own subjective experiences. The reviews investigate how and when the 3D scan data was used during the three simulation studies. By comparing the reviews, similarities and differences form the basis of the lessons learned that are presented with the hope of guiding the continued work in this area.

This paper is divided into six additional sections. The state of art in the field of 3D laser scanning is presented in section 2, which is followed by the approach of how to apply 3D laser scanning in simulation studies in section 3. In section 4, the three simulation studies are described and the lessons learned from these studies are presented in section 5. Finally, section 6 presents the discussion and future work followed by conclusions in section 7.

2 3D LASER SCANNING

3D laser scanning or LAser Detection And Ranging (LADAR) is a non-contact measurement technology designed to capture spatial data. The technology was developed within the field of surveying as a tool to map terrain as well as to control and monitor the status of construction jobs. Today, 3D laser scanning is used in a variety of fields, such as tunnel and road surveying, building and construction, archeology, robot cell verification, layout planning, and Forensics (Slob and Hack 2004; Sansoni, Trebeschi and Docchio 2009; Jaselskis, Zhili and Walters 2005; Lerma et al. 2010).

When capturing spatial data with a 3D scanner, the scanner is placed within the environment of interest; this could be an existing production system or a brown field factory floor. Laser light is emitted and directed across the surrounding environment and its reflection is detected to determine the distance to the reflecting object. Today's scanners are able to sample their entire field of view in a matter of minutes with a positional accuracy of a less than a centimeter (FARO 2013). The resulting data is often referred to as a point cloud, a set of coordinates in 3D space, typically numbering in the tens of millions of data points. Some 3D scanners are equipped with RGB sensors to add color information to the coordinates to further improve visualization. In Figure 1 a comparison of two views of the same system can be seen, one of CAD data and one of 3D scan data.

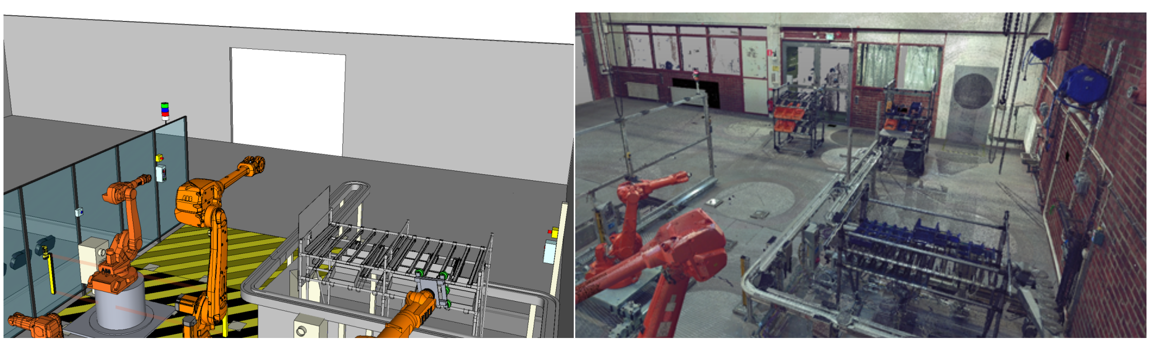

Figure 1: Comparison of traditional CAD data (left) and 3D Scan data (right).

As the 3D laser scanning technology matures and spatial data capture become more readily available there is also a steadily growing range of software tools to support data usage and analysis (Bi and Wang 2010). Typically, these tools are either specialized to visualize and edit point cloud data sets or they are extensions of traditional CAD and simulation tools with added functionality to integrate point cloud data. The integration into existing tools enables hybrid modeling environments where CAD and point cloud data are used in conjunction. Using hybrid models, CAD models of new machine equipment or products in design stage are put into existing scanned production facilities for planning verification. The simulation studies presented in section 5 are examples of integration of point cloud data into CAD based simulation software.

A number of challenges with 3D laser scanning technology have been identified. Amongst them are the size of the data and the related additional processing and storage resource requirements (Bi and Wang 2010). Furthermore interoperability between vendor-specific software and data formats is an issue (Huber 2011). However, several research efforts strive to automate translation of point cloud data into CAD surfaces to reduce data size (Bosche and Haas 2008, Huang et al. 2009). Simultaneously the existing software vendors are integrating functionality for viewing and processing 3D scan data into their existing factory design and simulation suites. The standards community are responding in kind and ongoing efforts aim to develop neutral data processing algorithms and data formats to ensure repeatability, traceability and interoperability when working with point cloud data (ASTM 2011).

3 ON THE STEPS IN A DES STUDY

DES models can represent a wide range of systems (Banks et al. 2005). Commonly modeled systems are service centers, airports, public transportation, and industrial production systems (Banks et al. 2005). DES models rely on a set of states connected by logic functions (Banks et al. 2005). The states evolve interdependently through the triggering of events as the model is executed (Banks et al. 2005). Each event occurs at a discrete, scheduled time and often causes the scheduling of subsequent events (Banks et al. 2005). DES models are typically created to mimic a real world system in order to evaluate changes and predict the real world system's behavior over time (Banks et al. 2005).

DES is a mature technology and several authors have described systematic methodologies for carrying out DES studies (Banks et al. 2005, Law and Kelton 1991). These methodologies have common steps such as (Musselman 1994):

1. Problem formulation
2. Model conceptualization
3. Data collection
4. Model building
5. Verification
6. Validation
7. Analysis
8. Documentation
9. Implementation

The steps in a DES study are carried out in approximately the same order as the list above (Banks et al. 2005). Some steps could overlap and some steps are iterated. Overlap can occur e.g. when data collection continues during model due to time constraints (Banks et al. 2005). Iterations happen for example if the analysis step fails to meet the problem formulation, which generally requires rebuilding the model which potentially requires new data (Banks et al. 2005). From here on out, this paper will use the term *simulation* as synonymous to DES.

4 DESCRIPTION OF THE REVIEWED SIMULATION STUDIES

The three simulation studies were carried out in laboratorial and industrial settings during the years 2012 and 2013. As presented in Table 1, the studies had different purposes and scope in terms of area of interest. These factors affected how the scanning processes were carried out and how the scan data was used during the simulation studies. The scanner used for spatial data capture in each of the studies was a FARO Focus 3D 120 phase shift laser scanner. The resulting datasets were processed in FARO Scene before being used in the studies. The scan data was provided in the studies as support for the simulation engineers. How the data was used differed between the studies, in the following sections is a general description of the studies and how the data was used in each of them.

Table 1: Simulation studies outline and 3D scan details.

Study	*Simulation study A*	*Simulation study B*	*Simulation study C*
Purpose	Proof of concept and efficiency evaluation.	Visualization and evaluation of workflow and future layout.	Simulation of performance measurements and 3D for visual likeness.
Area of interest	Approx. 190 m^2	Approx. 800 m^2	Approx. 20 m^2
Scans	8 scans	13 scans	6 scans
Time to scan	Approx. 2 hours	Approx. 4 hours	Approx. 1 hour
Scan data size	Approx. 1700 MB	Approx. 2500 MB	Approx. 900 MB

4.1 Simulation Study A

Simulation study A was carried out in a laboratory setting consisting of mainly a robotic cell and an assembly line. The purpose of this study was to make a proof of concept and evaluate the use of 3D scan data to support the simulation engineers. Using the simulation model, a proposal for reorganizing the area to incorporate a machining operation was presented. The simulation model contains a mix of automation, three industrial robots, a closed loop conveyor belts, and two manual work stations. This simulation model included inflow and handling of material, manual assembly, and automated operations.

The simulation engineers were located in the direct vicinity of the production area and had access to the system at will. 3D scan data was captured for the production area and used as a spatial measurement data source for designing the proposed system set up. The 3D scan data allowed the simulation engineers to locate objects in the simulation model and verify and measure their positions. The scanned robot artifacts were replaced by robot simulation objects in the simulation software while the scan artifact of the conveyor belt was directly overlaid with movement paths to model the conveyor belt's logical attributes. As can be seen in Figure 2, the scan data of the surrounding environment was kept as graphics in the model.

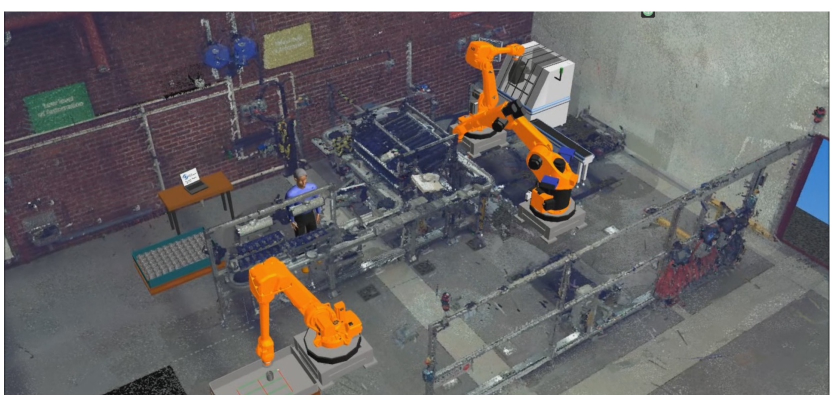

Figure 2: The simulation model of Simulation study A.

4.2 Simulation Study B

Simulation study B was carried out in a factory producing engine components for the aerospace industry. Prior to the study, a robotic x-ray cell for automated quality control of the produced components had been installed. Due to increased production volumes, the company was required to increase the capacity by installing an additional identical cell. The purpose of the simulation study was to visualize and analyze the workflow and future layout around these two cells.

The area around the existing cell was scanned and used to support the simulation engineer when creating the simulation model. The scan data was used for three different purposes. First, to evaluate the space required for the new cell by duplicating the first cell and placing it at the planned location within the point cloud model. Second, to improve the level of visualization in the simulation model using point clouds to represent static parts of the factory. Third, to use point clouds when creating 3D CAD models for parts with kinematics to be used in the simulation model. Such parts were for example the overhead crane and wagons used for transporting x-ray films. The resulting point cloud based simulation model, as presented in Figure 3, visualized a possible layout considering the workflow including machine operators and material transportation.

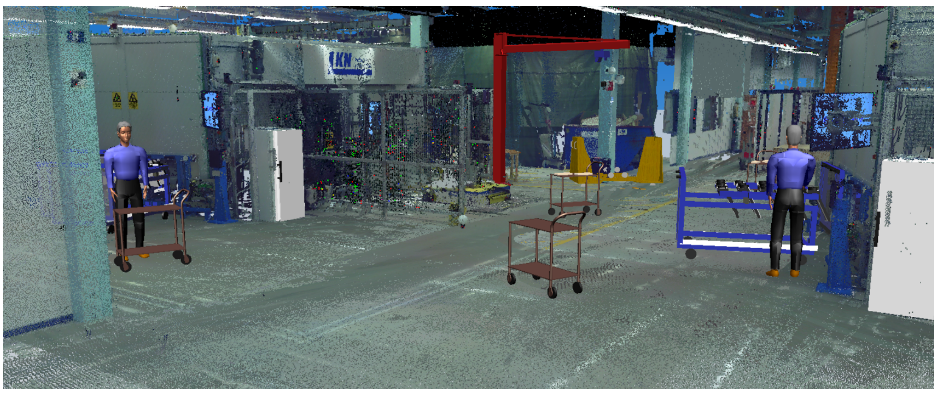

Figure 3: The simulation model of Simulation study B.

4.3 Simulation Study C

The object of simulation in *Simulation study C* was an automated pick and place and assembly cell built as an equipment control and integration demonstrator. The cell had been under physical development for several months when the simulation study was initiated and the simulation model development ran in parallel with the physical development until completion. The purpose of the simulation model was to provide a test bed for optimization of the physical cell. Key performance indicators (KPIs) such as utilization of the articulated robot and the Cartesian pick and place robot, as well as overall throughput were measured over time to better understand the effects of disturbances and failures on the overall system performance.

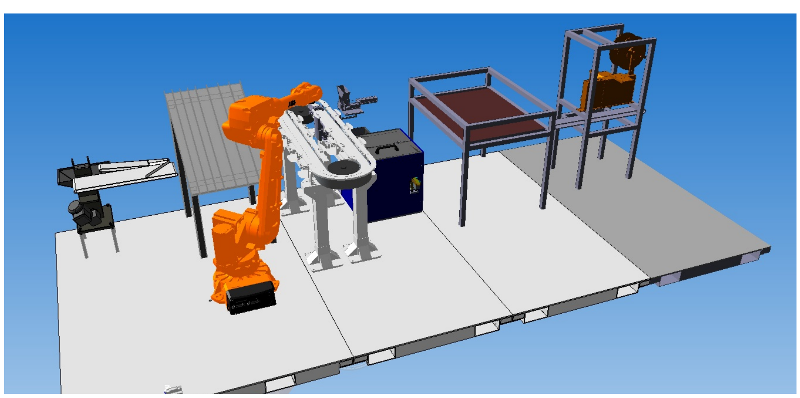

Figure 4: The simulation model of Simulation study C, without the display scene.

The physical cell, under development at the time, was 3D scanned to provide input for the simulation engineers as they developed conceptual model created from the geometries of the cell. Using the 3D scan data a CAD based simulation model was created, as presented in Figure 4. The display scene for the demonstration was scanned and inserted into the simulation model, adding a physical connection to the venue.

5 REVIEW OF THE SIMULATION STUDIES AND LESSONS LEARNED

This section presents a structured review of each of the three simulation studies presented in section 4, followed by a combined analysis of said reviews. The reviews lend their structure from the generic simulation study method described in section 3. The analysis combines the three reviews into lessons learned which aim to guide future efforts in this field.

5.1 Description of Reviews

The reviews showed that the 3D scan data were used differently in the three simulation studies, see Table 2. Note that, for some simulation study steps, the 3D scan data was not used in any of the reviewed studies. In the following sections, the findings from reviewing the studies are discussed from the point of view of a simulation engineer.

Table 2: A summary of the addressed steps in the simulation studies, an X indicates that the 3D scan data was used in the corresponding simulation study step.

Simulation study step	*Simulation study A*	*Simulation study B*	*Simulation study C*
Problem formulation		(X)	
Model conceptualization	X	X	X
Data collection		X	
Model building	X	X	X
Verification			
Validation		X	
Analysis	X	X	
Documentation	X	X	X
Implementation			

5.1.1 Problem Formulation

For each of the three simulation studies the problem formulation was initiated before any scan data was captured. However, in *Simulation study B*, the simulation engineers decided to conduct the 3D laser scanning and use the results to guide the ongoing process of refining the problem formulation. The initial problem formulation asked whether it was possible to install an additional robotic x-ray cell in a specified area. Using the 3D scan data the problem was refined to optimizing the orientation and exact location to facilitate parallel loading and unloading of both x-ray cells by on team of operators.

5.1.2 Model Conceptualization

In each of the three simulation studies the scan data was utilized as a remote view of the system. Especially for *Simulation study B* and *C*, where the simulation engineers were located away from the production systems. In *Simulation study A*, a number of early concept could be visualized using the 3D scan data to solicit feedback from users of the system.

5.1.3 Data Collection

In *Simulation study B*, the possible to explore the scan data depicting the current state of the production system was utilized to plan on-site data collection activities, e.g. time studies and work task mapping, in advance. This planning and the improved familiarity with the site reduced the time required for data collection on-site.

5.1.4 Model Building

In the three simulation studies 3D scan data was used both to position objects and represent the surrounding factory environment, as exemplified in Figures 2 and 3. In *Simulation study B* and *C*, 3D scan data provided spatial measurements of equipment which was subsequently used to reconstruct CAD objects in the simulation model. In *Simulation study A* an approach to directly using a scanned object as a simulation object was realized by adding movement paths, stations, and sensors to the scanned conveyor system.

In *Simulation study A*, some time savings where gained by simply adding movement logics directly onto the scanned conveyor. In this way no measurements were necessary to replicate the conveyor using generic model library objects.. Both *Simulation study A* and *C* used the scan data extensively during the model building. *Simulation study A* used the 3D scan data as part of the model and both studies used 3D scan data to replicate objects in CAD format.

5.1.5 Verification and Validation

None of the three simulation studies can be said to have specifically made use of the scan data during model verification. However, there is an element of layout verification during the model building if the scan data is used during that step.

In *Simulation study B* the simulation model was created in very close access to the simulated system. In *Simulation study C* the model had been translated into CAD data which was used for communication and verification with the subject matter experts.

5.1.6 Analysis

In *Simulation study A* and *B*, the models where visually inspected to verify feasibility of the future states. In *Simulation study C* the physical placement of robots where iteratively evaluated considering reachability and obstructions from the surroundings. In addition, *Simulation study C* modeled human movements while handling material and operating the control system based on the 3D scan data.

5.1.7 Documentation

If the 3D scan data is part of the stored simulation model it can act as a digital 3D imprint of the production system as it was configured at the time of the simulation study. However, 3D scan data requires more storage space than traditional 3D CAD models, see Table 1 for examples of data size. This limits the possibilities of storing numerous versions of a scanned area and makes the sharing of models less convenient. The 3D scan data can be used for realistic visualization in the documentation such as screen shots and video renderings of the models.

5.1.8 Implementation

None of the models created in the three simulation studies have been used for implementation at the time of this publication.

5.2 Lessons Learned

In Table 3 below is a summary based on the reviewed studies. The recommendations provide an indication to what should be considered when incorporating 3D laser scanning in a simulation study.

Table 3: Considerations and recommendations for using 3D scan data in simulation studies.

Simulation study step	**Considerations and recommendations**
Problem formulation	3D scan data seems to be beneficial as visualization support for the current system during project startup meetings. If no 3D scan data is available at this point, the problem formulation could help guide what area, if any, that needs to be 3D scanned.
Model conceptualization	3D scan data provides a remote view of a system, enabling visual inspection from any angle and a platform for discussing functionality and logical connections. The remote view can lead to reduced travelling and need to be on-site as reviews can be performed remotely.
Data collection	Time on-site is limited and the efficiency and quality of the data collection stages relies heavily on planning. In this respect the scan data can provide a good basis for planning and simultaneously familiarization with the environment.
Model building	The 3D scan data can act as a blueprint of the production system in the model building step, provided that there is a pre-existing production environment. The 3D scan data can be used either as backdrop to the simulation objects or as reference data for creating CAD simulation objects.
Validation	The added visual likeness can potentially help to communicate the model to production system users and subject matter experts and in so doing facilitate the validation process.
Analysis	If conducted properly, 3D scanned measurements of the work environment ensures a level of positional accuracy below a centimeter. For analysis of manual work ergonomics and design this accuracy is considered sufficient.
Documentation	Due to the high level of visual likeness the recognition factor for persons familiar with the simulated system, so even after some time the simulation model can be understood. Similarly, in a study that proposes a change to a production system, the future state presentation can be aided by the 3D scan data. The increased file size caused by 3D scan data can make storage and sharing of models more resource demanding.

6 DISCUSSION AND FUTURE WORK

The work described in this paper looks at experimental uses of a 3D laser scanning in only three studies. A well-known issue with this type of experiment and intervention heavy research approach is the difficulty to verify the effects of the intervention. There is no control group or reference to compare the results to. There is no way to determine what would have been different if these three studies would not have utilized 3D laser scanning as part of the work. Also, as the studies are reviewed in retrospect based on documentation there are a number of known and unknown uncontrolled parameters which have affected result of the studies. One can question why 3D laser scanning is not more widely used for simulation of production systems? One factor is undoubtedly the lack of simulation software support for visualization of 3D scan data. Although 3D scan data of a system can still be used to communicate with subject matter experts and to gather positional data for layout of simulation objects.

The next step of this work will look to further distinguish which usage areas within a simulation study that stands to benefit the most from the integration of 3D laser scanning. To do this more studies will have to be conducted and/or reviewed, ideally a way to test the effects from using 3D scan data should be tested in controlled setting. The long term goal will be the creation of a framework for the integration of 3D scan data in simulation studies.

7 CONCLUSIONS

Reviews of three simulation studies in the field of production systems and incorporating 3D scan data shows that most of the steps in a simulation study can be supported by 3D scan data. The main benefits of using 3D scan data were identified as comprehensive visualization and the ability to conduct spatial measurements at will. The comprehensive visualization facilitate communication with non-simulation stake holders. The capability to take measurements without being on site will potentially reduce the need for travel. Finally there is a need for structured work methods to make the most out of the use of 3D scan data in a simulation study.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement No. 609027 (Project Use-it-wisely).

This research is also partly 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.

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