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Production system geometry assurance using 3D imaging

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Abstract

Production systems evolve to accommodate new and redesigned products. These changes are planned offline in virtual tools, to reduce disturbances on ongoing production. Offline planning requires virtual models that correctly represent reality. Most models are "as-designed" and suffer from geometrical errors stemming from deployment alterations. Such errors are often discovered late in the next change process or during installation, making corrections expensive. Having geometry assured production systems and models eliminate one source of error during the production system change process. This paper evaluates 3D imaging and the C2M (cloud-to-mesh) algorithm for assessing the validity of virtual production system models.

Keywords: 3D imaging; 3D laser scanning; Geometry assurance; Production systems

1. Introduction

Production systems exists to realize product designs. For some companies, the production system and its capabilities constitutes the core competence and value asset. For others, it is merely a means to producing a sellable item. Regardless of which, the production system needs to adapt and develop over time. In the former case, it is to keep ahead of competitors that would like to replicate the capabilities. In the second case the product design will change and be replaced my new products, requiring upgrades and changes in existing production systems.

In both of the outlined examples, efficient and reliable operation of the production system is a key enabler to being profitable [1]. This extends to the requirement of keeping machines and production processes online and running as much as possible. To still allow for changes and adjustments, offline planning and design of the changes has emerged as a best practice. Enabled by computer system development and digitalization, companies are able to program i.e. control systems and robots in the virtual world before implementing them on the physical production system. Thus it is possible to detect and manage problems offline and reduce the disturbances and downtimes in the physical production system [2]. It has also allowed for virtual implementation of production system functions and capabilities based on early product designs [2]. Letting production engineers feedback manufacturing related design flaws to design engineers prior to the existence of any physical prototypes and/or tools.

One key aspect of such models is the geometrical likeness to the physical world. The models need to be correct representation of the real world to enable activities like e.g. tool design, collision detection, robot path programming, and ergonomic analysis to be carried out virtually. Currently, product geometries and equipment geometries are often well defined and available in a digital format. This is generally not the case for models of the context of the production system. By context we refer to the building that houses the production and other pre-existing machines in adjacent production flows or cells. Such data may exist but is often incorrect due to undocumented changes over time, inaccuracies in the original data, or errors during the construction of the building or installation of the equipment.

Many technologies exist within the area of 3D imaging, to capture spatial data on different levels [3]. It can be used to

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measure, with great detail and accuracy, the physical output of a production process and validate it is geometry to the intended design model [4]. It can also be used to capture measurement data of rooms and spaces, making their physical properties available in a digital format [5]. This data is often referred to as point clouds, implying their contents, which is essentially a cloud of coordinates sampled off of the surfaces of any and all objects in the measured environment. These point clouds represent, within a few millimeter, the spatial configuration of an existing environment, such as the building or production system in a factory. This data can be used to plan installations, follow them up as they proceed to verify the steps, and once the installations are done validate that the installation was carried out according to plan in terms of positioning in 3D. Having geometry assured production systems and models eliminate one source of error during the production system change process. Fig 1. gives an overview of the relationship and usage of CAD data and 3D imaging.

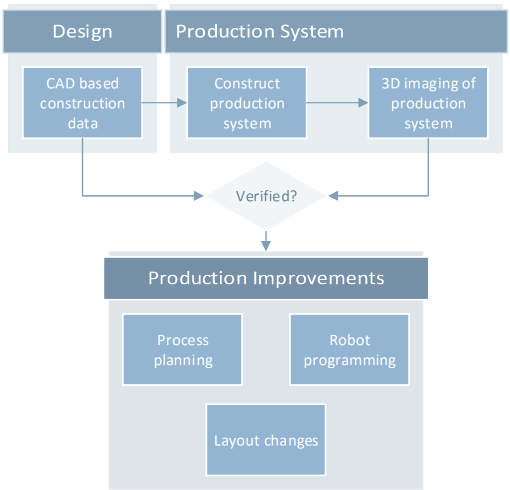

Fig. 1. Overview of usage of CAD data and 3D scanning

This paper describes two cases where a C2M (cloud-to-mesh) algorithm is applied to quantitatively assess installed equipment against the digital blueprint. Based on the results of the comparison we discuss the applicability of 3D scanning and C2M measurements as an approach to assess the accuracy and correctness of production system CAD models. Deviations in the models are categorized based on a framework for errors in CAD data. To conclude we discuss the implications of found deviations and how to handle them, based on type and criticality.

2. On 3D imaging

3D imaging is a technology with many application areas. Machine vision, cartography, archeology, crime scene investigation are some examples [6, 7, 8, 9]. This section will discuss the current state of 3D imaging in relation to manufacturing applications. It will also act as an introduction to spatial digitalization through 3D imaging and more specifically 3D laser scanning.

2.1. 3D imaging

The ASTM Subcommittee E57.01 on *Terminology for 3D Imaging Systems* defines 3D imaging systems as [10]:

"*a non-contact measurement instrument used to produce a 3D representation (e.g., point cloud) of an object or a site*"

There exists a multitude of measurement instruments for 3D imaging. Several surveys of the field exists to classify and describe available technologies for 3D imaging [11, 12]. Table 1, below presents one such classification.

Table 1. Categorization of 3D imaging techniques [12].

Light waves 100 to 1000 THz			
Triangulation (sine law)		Time delay (speed of light & light coherence)	
Passive	Active	Time-of-flight	Interferometry
Photogrammetry	Projection: single spot	Pulsed (Lidar)	Holographic
Focus/de-focus	Projection: sheet of light	Continuous modulation	Multi-wavelength
Theodolite	Projection: Bundle of rays		Speckle or White light based

2.2. Sources of errors in 3D imaging

Accuracy and uncertainty are key for understanding the quality of a 3D image in terms of usefulness for various analyses. However in general the human impact is smaller than when CAD models are used. Beraldin et al. [12] presents a fishbone diagram over the uncertainty contributors in 3D imaging, see Fig. 2. The sources are divided into six main categories: Method, HW Means, SW Means, Ambient, Material, and People. Each one contributes to the accuracy and the reliability of the captured data.

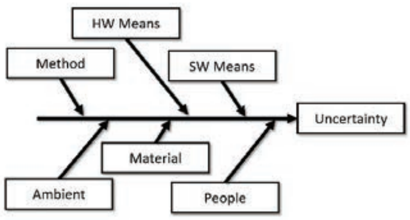

Fig. 2. Fishbone depiction over sources of uncertainty, adopted from Beraldin et al [12].

There are bound to be uncertainties and errors in any type of model. In the field of product Geometric Design and Tolerancing (GD&T) there are examples of taxonomies over such errors. This paper follows a definition from MacKinnon and Carrier [4], who present five main categories of errors, form, size, location, orientation, and profile. The definition has been altered to better fit the production system model application. The final category, Profile is substituted for object mismatch, Indication whether or not a feature exists in the captured data but not in the model.

2.3. Sources of error in 3D laser scanning

In 3D laser scanning specifically, these errors are also existing and different devices produce different accuracy. There is research aiming to determine accuracy of 3D laser scanning [13]. And for example the American institute: National Institute of Standards and Technology (NIST) has set up a test site to standardize performance of 3D scanner devices [14].

Regardless of what device is used, the two most prevailing sources of error, pertaining to the data quality are arguably shiny surfaces that deflect the laser and edge effects (often referred to as stray points). Shiny surfaces result in laser beam diffraction and returns from secondary surfaces. This can be circumvented by applying a non-reflective coating, often as a powder or spray to any shiny surfaces. Edge effects are an artefact that stems from the laser beam reflecting of off two spatial separated surfaces simultaneously. It is prevalent when the laser travels across an edge during the instance of distance capture.

3. CAD documentation of production systems

CAD is used to model the production system throughout its life cycle. Before it is physically conceived there are construction drawings, detailing its components and their positions. During its operational phase there are drawings used as baseline for system changes, and for reference when discussing things related to its operation. These drawings are created and maintained by engineers. The plans are sometimes created by external contractors and delivered upon installation of equipment. The latter are more likely kept and maintained by an internal function placed in the maintenance or facility management unit of the company. The means by which these drawings are created and maintained has changed over time. Historically measurements were captured using rulers, this progressed into laser based measurement devices. Machines and other operational equipment are often drawn as part of their design process and can be extracted as 2D layout objects at a suitable level of detail.

When it comes to CAD models very little literature talks of explicit errors, such as misplacing components or omitting parts. The errors that are mentioned pertain to geometrical errors in surface [15] or errors that occur during automated model simplification operations [16]. Yang, 2006 classify and determine the frequency of occurrence for six types of errors in CAD models [17].

These examples concern the ability of CAD models to accurately represent geometrical shapes in a consistent and unambiguous way. They do not so much relate to the types of modeling errors related to position or inclusion/exclusion of objects that are critical in the planning or modelling in a production system design [5].

4. Method

To be able to compare the existing CAD models with the real world, a 3D imaging technology for indoor environments was used. Fig. 3 visualizes the phases that were covered, the final stage adjust reality, or adjust model has not been implemented as of now but will still be discussed in section 6.

Fig. 3. Principal steps of the method used for assessing the accuracy of the CAD model

4.1. Capture Spatial data

For this step 3D laser scanning was used. 3D laser scanning is suitable for covering comprehensive spatial data collection of production environments [5]. The industrial cases were chosen based on availability and interests of companies nearby. The scanner available to the research group was a FARO Focus 3D. Data collection was conducted on site by the authors during stoppage in ongoing production. For the comparison, CAD data corresponding to the scanned areas was provided by the companies involved.

4.2. Process Spatial data and align to CAD

The captured spatial data was processed in the commercial software provided with the laser scanner, FARO Scene [18]. The processing involved noise cleaning and registering multiple scans into one data set. The data was partitioned to cut away any captured points outside of the cell area. The decision on what was included in the cell area and not was guided by company engineers. The cleaned and registered data was exported in E57 format, a neutral file format designed for measurement data [19]. For the remainder of the processing and comparison the open source software Cloud Compare (CC) was used [20]. For CAD data, the files received from the companies was exported in .stp format as it provides a neutral data format. From the .stp a transformation was made to .ply to facilitate use in CC which then was used for comparison with scan data.

Both the scan data and the CAD model was imported into CC. If needed there is an alignment process to fit the data sets together. It this case one CNC machines corner point was used, and for the larger cell the conveyors were overlaid.

Following the alignment of the CAD and measurement data, the scan data was down sampled using the random sample algorithm in CC [20]. This was done to facilitate computations and reduce duration. A suitable size was deemed to be 250000 points.

4.3. Compare

The cloud-to-mesh (C2M) feature in the CC software was used to compute the distances between the captured data points and the meshes of the CAD model [20]. This was done to quantitatively gauge how well the CAD data complies with the captured data. The algorithm returns the distances between every data point and the closes surface along the normal vector as a scalar field. The scalar values was then used to colorize the point data. Blue was used for compiling data and yellow followed by red for increasingly deviation data.

4.4. Assess deviations

The scalar field was also used to visualize the compliance in a histogram format using .xls. This histogram can help by classifying the amount of complying data and possibly direct efforts to improve models. What levels are acceptable was not addressed.

5. Description of experiment setup and results

The approach was evaluated at two companies in their manufacturing systems. The environments used differed quite distinctly. In Case A, the comparison was done on a complex production cell, containing several conveyor belts, a weld gun, and two industrial robots and vision systems. In Case B, the subject was an enclosed CNC machine and it is auxiliary equipment. Both setup and the results of the comparisons will be described in detail in this section.

5.1. Case A: Complex production cell

The alignment was necessary to be performed manually as neither the CAD nor the captured data was aligned to the factory coordinate system. The conveyors were used for alignment purposes. In Fig. 4 the visual results from the comparison can be seen.

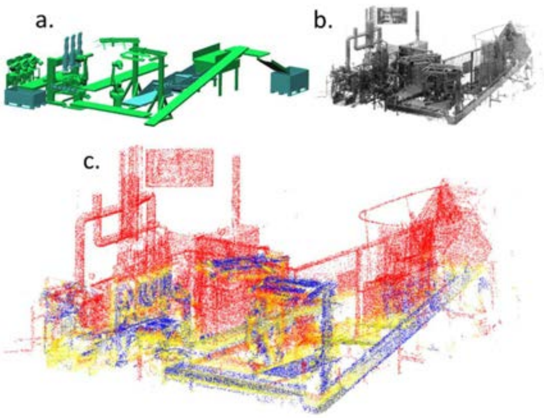

Fig. 4. Case A: complex cell. a. CAD model of the cell. b. Captured measurements of the production cell. c. Comparison results, blue points are within 20mm, yellow are within 80mm, and red points are outside 80mm.

Already when visually comparing the data in Fig.4 a. and b. it is clear that a larger portion of the cells contents is omitted in the CAD data. This is OK if the abstraction level in the CAD model was purposefully kept low. However, also the parts that do exist deviate in e.g. position and orientation.

In Fig. 5 the histogram over the C2M results is presented. Only about 10% of the measurement data is found within 20mm of the CAD model surfaces, represented by the blue coloring in Fig 4c.

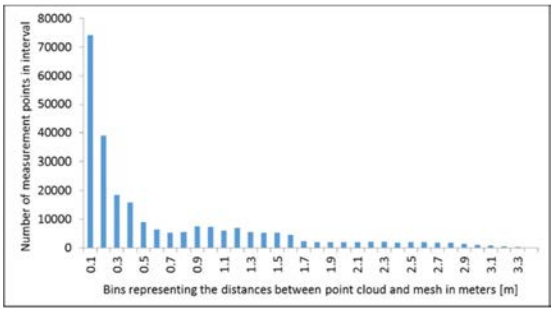

Fig. 5. Histogram over the calculated distances between CAD and point cloud data in Case A

5.2. Case B: CNC Machine

In Case B the machine position was correct except along one horizontal axis. To achieve alignment the model was moved until the outer wall was level with the captured scan data of the wall. In Fig. 6 the visual results of the comparison is presented.

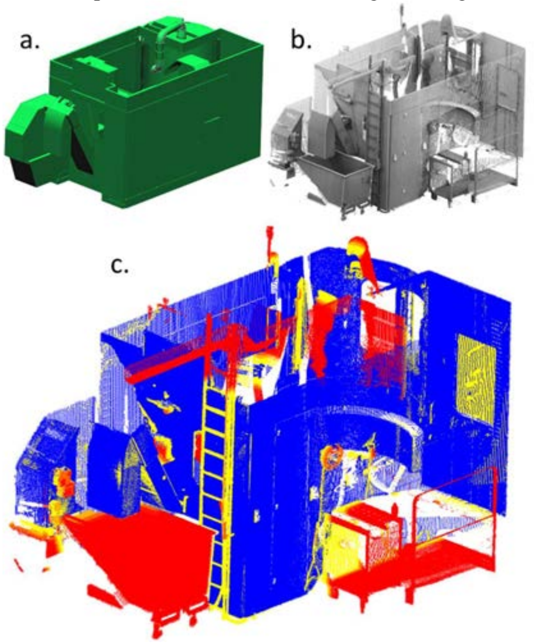

Fig. 6. Case B: CNC Machine. a. CAD model of CNC Machine. b. Captured measurements of the machine. c. Comparison results, blue points are within 20mm, yellow are within 80mm, and red points are outside 80mm.

The comparison yielded better results than in Case A. the main deviations are a result of things not being included in the CAD model. Examples are the cutting chips bin and the access ladder, as seen in red and yellow. The histogram over the C2M results, show in Fig. 7 indicate that the data is more consistent. About 48% of the captured data is within 20 mm of the CAD surface, represented by the blue coloring in Fig. 6c. It should be noted that the histogram bin size differs from Case A, and was adapted to the scale of the C2M results for better visibility of the histogram shape.

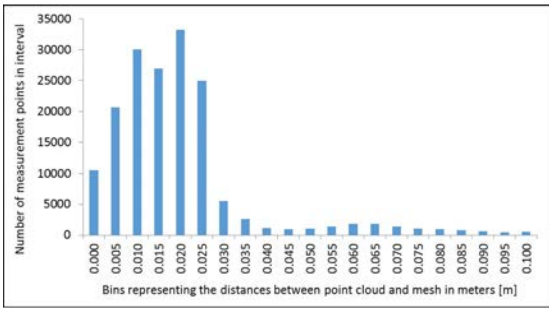

Fig. 7. Histogram over the calculated distances between CAD and point cloud data in Case B.

5.3. Summary of the Cases

In Table 2 below the existence of the different types of error according to the modified categorization of MacKinnon and Carrier [4].

Table 2. Occurrence of error categories based on the detected errors in the Case A and Case B.

	Case A	Case B
Form	Vision systems are configured differently than in CAD. Conveyors are at different angle	Shape of existing parts are OK
Size	Sizes seems to be OK	The main body of the CNC model is verified by measurements.
Location	The position of conveyors and robots deviate.	Location is OK
Orientat-ion	Vision system is installed at different angles.	Orientation is OK
Objects	Many of the objects in the captured data are missing in the CAD. e.g. fences, electrical cabinets.	Metallic grain bin, access ladder, auxiliary equipment and air evacuation vent were missing.

Case A of the complex production system has more errors, in more categories. It can be expected that the bigger the model is and the more objects it consists, the more errors it will consist. In Case B the main portions of the CNC machine are correct within 20mm of the CAD model. Some parts that were captured with the 3D imaging systems did not exist in the model. Such as the Metallic grain bin, access ladder, and air evacuation vent.

In addition to the model errors we should consider errors stemming from the 3D imaging system. Fig. 8 and Fig. 9 show examples of 3D scanning errors that occurred during the capture. These are artefacts of the specific 3D imaging system, as described in section 2.3 and introduce false deviations in the C2M computation results. Several methods for filtering these artefacts exist but were not employed in this work. For more consistent and accurate implementation of a comparison approach such as the one described in this paper, the effect of these types of measurement errors needs to be mitigated.

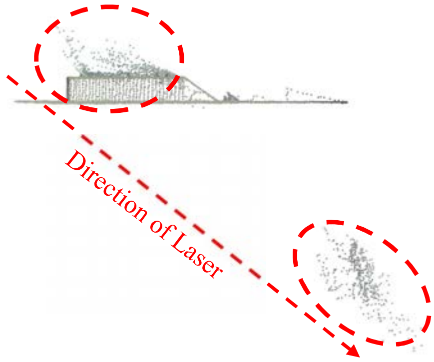

Fig. 8. Side view of shiny metal plate positioned on floor, scanned from above left. Error points occur around surface and below floor due to reflections.

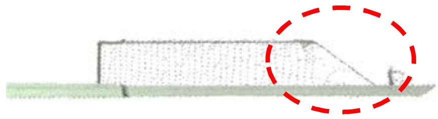

Fig. 9. Metal plate positioned on floor, scanned from above left. Edge effect occurs as a slope on the right hand side.

6. Discussion

For a manufacturing company there is also a need for a course of action to deal with the results stemming from the presented technologies. Two possible outcomes are given by a geometric comparison of the as–designed (CAD) models and the real system (measurements). I: the real system (measurements) sufficiently corresponds to the modelled system (CAD). II: The real system (measurements) deviates from the modelled system (CAD). If, as in case II, there exists a difference it has to be characterized and assessed to determine which if any course of action to take.

Again, two options are available. First one is to accept the installed, real system as the current state and update the model accordingly. Second is to correct the differences in the real system so that it corresponds well enough to the model. In both cases the models can again be used for decision making in day to day activities and planning of the future state.

The choice of which route to take will most likely depend on several aspects. Are the model-to-reality discrepancies critical or non-critical from a functional point of view? In the case of product models the concept of functional interfaces and surfaces exists and dictate the demands on tolerances. These are critical as they are the foundation for modularity and interoperability. A parallel can be argued in the of production systems. For example there exists interfaces between production lines, cells, or equipment. These need to be up to date to allow development of adjacent functions in a virtual model.

Further investigations into the topic should seek to find decision bases for what to do in the case of discrepancies. Our observations during this work implies that:

- Companies need a strategy for deciding if the deviation is acceptable or not is of interest.
- Criticality rating of the errors should be based on the intended usage of the CAD models.
- Manual work areas are likely less critical than areas where AGVs or robots operate.
- More examples and cases on various applications within the production systems are needed to guide implementations of the approach investigate in this paper.
- There is potential to automate the principal steps described in this study, which could lead to automation of virtual model verification.

7. Acknowledgements

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