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Toward a Digital Twin for real-time geometry assurance in individualized production

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ABSTRACT

Simulations of products and production processes are extensively used in the engineering phase. To secure good geometrical quality in the final product, tolerances, locator positions, clamping strategies, welding sequence, etc. are optimized during design and pre-production. Faster optimization algorithms, increased computer power and amount of available data, can leverage the area of simulation toward real-time control and optimization of products and production systems – a concept often referred to as a Digital Twin. This paper specifies and highlights functionality and data models necessary for real-time geometry assurance and how this concept allows moving from mass production to more individualized production.

1. Introduction

A highly automated production factory for complex assembled products is a huge investment and return on investment requires high product quality, factory throughput, equipment utilization, and flexibility as well as low energy consumption. Geometry related problems, resulting in late changes and delays, usually constitute a significant part of the total cost for poor quality.

1.1. Geometry assurance

Geometry assurance can be described as set of activities that contributes to minimizing the effect of geometrical variation in the final product. Activities take place in all phases of the product realization loop, see Fig. 1.

The design phase: Here, concepts are analyzed and optimized to withstand manufacturing variation. Product requirements are defined and decomposed into locator positions and tolerances on pars and subassemblies.

The pre-production phase: Here, the product and the production system are verified physically. Adjustments are made to correct initial errors and prepare for full production. Inspection preparation and off-line programming of coordinate measurement machines and scanners are performed and all inspection strategies and inspection routines are decided.

The production phase: Here, all initial production process adjustments are completed and the product is running in full production. Inspection data from parts and subassemblies are used to control production and to detect and correct errors.

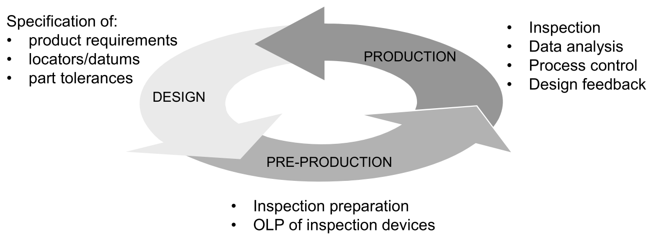

Fig. 1. The geometry assurance process.

Most companies today are fully aware of the fact that a change is costlier in production than in the design phase. An effective digital geometry assurances process has the potential to drastically reduced costs and adjustments in production [1].

1.2. Digital Twins

The area of virtual/digital development of products and production systems has grown extensively the last 20 years. Simulation and optimization are today used for a variety of different products and development tasks. Simulation has been an important tool for shifting expensive product changes, often discovered during production start, to earlier design phases where cost for change is low. Increased number of model programs with shorter intervals drive the needs for simulation. The ability to simulate production ramp-up therefore becomes increasingly important [2].

Increased computer power, faster algorithms and more efficient optimization routines have made simulation and optimization an everyday tool for engineers. Calculation time has gone from weeks

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to hours and minutes which have made it possible to, not only verify solutions, but also to explore the solution space, searching for the global optimum. Increased focus on sustainability, with reduced waste, is also a driver for a more global view on optimization of design and manufacture [3].

Traditionally, simulation has been used in the design phase with estimated or historical data as input. Increased use of sensors and in-line measuring equipment are making it possible to use (and reuse) simulation models created during product development also in production, now with real data as input. This will allow for adjustment of machine settings for the next product in line based on simulations in the virtual world before the physical changeover, reducing machine setup times and increasing quality. The ability to link large amounts of data to fast simulation makes it possible to perform real-time optimization of products and production processes. The concept of using a digital copy of the physical system to perform real-time optimization is often referred to as a Digital Twin. The concept of a Digital Twin was adopted by NASA for safety and reliability optimizations in [4] and [5]. With an aggressive push toward "Internet of Things", data has become more accessible and ubiquitous which necessitates the right approach and tools to convert data into useful, actionable information [6]. The vision of the Digital Twin itself refers to a comprehensive physical and functional description of a component, product or system, which includes more or less all information which could be useful in the current and subsequent lifecycle phases [7,8]. Simulation and seamless transfer of data from one life cycle phase to the subsequent phase are central for the concept of the Digital Twin.

The digital development advancements allow sensors, machines, workpieces, and IT systems to be connected along the value chain beyond a single enterprise. These connected systems (also referred to as cyber-physical systems) can interact with one another using standard Internet-based protocols [9] and analyze data to predict failure, configure themselves, and adapt to changes. Increased availability of data will also open up new possibilities for better maintenance and related service systems [10].

1.3. Scope of the paper

This paper proposes the concept of a Digital Twin for geometry assurance. The paper combines research within variation simulation and quality control to an autonomous self-adjusting system that optimizes quality and allows for individual production. The Digital Twin is developed and used for product and production system design in the concept phase and later on inherited for inspection preparation and process control. Functionality and information needed in each phase/step are specified. How the concept of the Digital Twin allows moving from mass production to more individualized production is discussed, as well as future research challenges.

2. The Digital Twin in the design phase

In the design phase, different product concepts are developed and optimized to withstand the effect of manufacturing variation. From a geometry assurance perspective, three basic activities are performed:

- Specification of product requirements/tolerances.
- Specification of locating schemes.
- Specification of part tolerances.

A Digital Twin, supporting robustness and tolerance analysis in the design phase, uses geometry representations of the parts, kinematic relations (locating schemes and transformation matrixes) in combination with FEA to perform sensitivity and variation analysis. The Digital Twin is fed with variation data for parts and fixtures, normally gained from similar earlier projects.

2.1. Functionality: locating scheme optimization

Locating scheme optimization is a critical step in geometry assurance. Variation propagates through the physical contacts (locating schemes) between parts and fixtures in an assembly. Locating schemes can be seen as representing the transfer functions between input and output variation and controls the robustness of a mechanical assembly. The stability analysis evaluates the geometrical robustness of a concept and shows how variation, introduced by the locators and the additional clamps, propagates and affects critical features and dimensions [11]. Fig. 2 shows variation for two different locating schemes (Concept 1 and Concept 2) used for joining before and after spot welding and release from the fixture. Only the master location schemes are shown. Additional clamp locations can be included in the same way.

2.2. Functionality: statistical variation simulation

Variation simulation can be performed by utilizing transformation matrices to calculate how part variation propagates in the assembly. The method is often combined with Monte Carlo (MC) simulation. For non-rigid variation simulation, finite element analysis (FEA) is included. The method allows over-constrained locating schemes that result in bending during assembly due to variation in parts and fixtures. The method of influence coefficient (MIC) [12] is used to reduce computational time. Contact modeling prevent penetration due to bending and deformation during assembly, see [13] and [14]. Fig. 2 shows non-rigid variation simulation in the software RD&T, where the color coding indicates the expected variation.

Lately, new materials with tougher requirements on bending, deformation and stress are introduced in aerospace and automotive industry. Variation simulation to verify geometrical deformation and stress criteria and to support shimming strategies are treated in [15]. A future challenge is how variation simulation can be performed fast enough for in-line use.

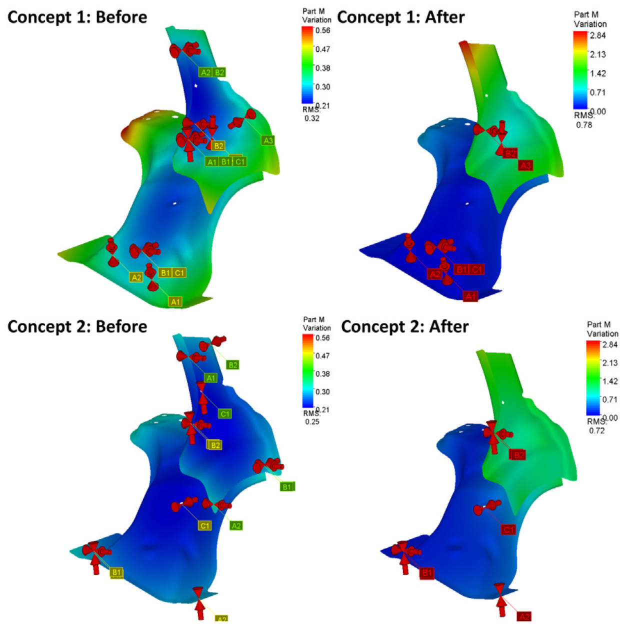

Fig. 2. Variation simulation of a two-part assembly.

3. The Digital Twin in the pre-production phase

In the pre-production phase, the Digital Twin is used as a basis for inspection preparation and off-line programming (OLP) of coordinate measure machines (CMMs) and scanners. It also contains the definition of the final inspection points and a link to the inspection database.

3.1. Functionality: inspection preparation

Based on the Digital Twin geometries and functionality, inspection features and inspection programs can be generated. Stability analysis and variation simulation can give valuable information about where to measure. Automatic collision free path planning can determine how to measure. This technology allows new inspection programs to be generated, or existing programs to be updated, in a time efficient way [16].

A fully automatic in-line inspection system was recently reported in [17]. The computational time to create a point-cloud from the captured images is about 30 s and the computational time for the comparison with the CAD-model is about ten milliseconds. This technology seems promising for in-line inspection and may well be combined with real-time process adjustment using the Digital Twin approach.

Cluster analysis can be used to reduce the number of inspection points from an initial large set of points to a smaller set of inspection points used in full production [18,19]. A future challenge is how scanning can be performed fast enough for in-line use.

4. The Digital Twin in the production phase

In the production phase all production process adjustments are completed and the product is in full production. In this phase, the virtual assembly model (variation simulation model) is used together with inspection data to control production and to detect and correct errors. Future possibilities to fast capture a large amount of data allow for in-line inspection, analysis and control of batches or even individuals, adding a new dimension to mass production.

4.1. Functionality: virtual trimming

During assembly of newly produced components, form errors can cause either functional or esthetical problems. Instead of compensating the tools, which is quite expensive, this error is compensated for by adjusting the locators. This is also known as trimming and is traditionally done manually and iteratively. A method for virtual trimming was proposed in [20]. Based on inspection data from initial components and the variation simulation model (the Digital Twin), all trimming activities are performed in the computer tool presented. After the locators are adjusted, the result is presented directly, which eliminates the need for physical inspection in order to verify the result of the trimming. The tool also includes optimization of the trimming. Efficient use is based on real-time data as input.

4.2. Functionality: joining sequence optimization

For non-rigid parts, the joining sequence is crucial for how variation in the individual parts, fixtures and welding equipment will affect the final assembly. Fig. 3 shows an example where the same two parts, with the same fixture (Concept 2 in Fig. 2), are joined together with seven weld points using two different sequences. As can be seen, one sequence results in quite large deviation (middle) while the other does not (right). In a sense, the latter can therefore be seen as the more robust one. Joining sequence optimization is treated in [21]. The in-plane position variation of the welding gun is treated in [22].

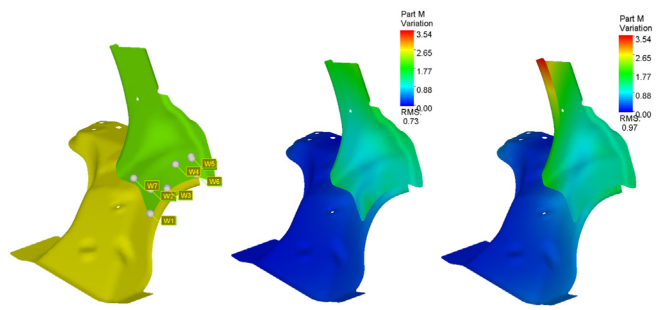

Fig. 3. The effect of joining sequence.

For many non-rigid assemblies, the force needed to close the gap between the parts is critical. For sheet metal assemblies, this may affect the size of welding gun needed and for assemblies with plastic parts it affects the size and type of clips used to join the parts [23]. For joining of dissimilar material, temperature is also quite important to consider [24]. Joining sequence optimization is dependent on real-time part geometry data.

4.3. Functionality: root cause analysis (RCA)

The assembly process for a complex product such as an automotive body is realized by a large number of fixtures in several stations. Fixture related geometrical errors, may in a complex assembly be difficult to identify. A number of fixture errors may occur that leads to similar deviations in the final assembly. A general approach and a tool for RCA that allows individual station, fixture and locator errors to be identified were proposed in [25]. The tool translates variation and deviation in geometry data to actions for adjustable process parameters. To separate variation caused by fixtures and the variation caused by previous and other manufacturing processes, a multivariate fixture failure subspace control chart is proposed [26].

During production, the Digital Twin is fed with inspection data from the final product. This is used to analyze if product errors originate from assembly fixtures and decide what fixture and what locators that have generated the error.

5. The Digital Twin – a sheet metal assembly example

In a highly automated production factory for complex assembled products there could be up to several hundreds of robots organized into lines and stations for handling and joining operations. Geometry related problems, resulting in late changes and delays, usually constitute a significant part of the total cost for poor quality.

To scan and analyze inspection data of parts and subassemblies fast and in real-time allow for new possibilities to adjust the process and the equipment to compensate for geometrical deviations of incoming parts. In Fig. 4, a concept for an autonomous self-optimizing robot welding station is proposed.

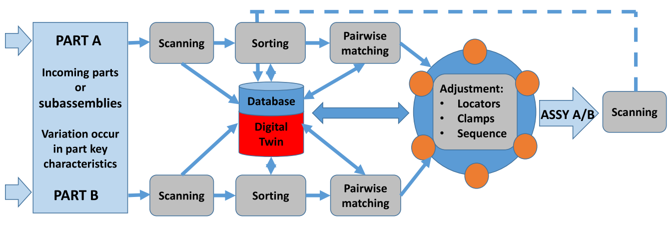

Fig. 4. Self-compensating assembly line.

The proposed concept is based on the idea of a Digital Twin, inherited from the design phase, containing all nominal geometries for the parts (FEA meshes) and the equipment (fixtures, robots and welding guns). The Digital Twin also contains mating conditions (and contacts modeling) as well as functionality for locating scheme optimization (Virtual Trimming), variation simulation, and welding sequence optimization. This basic functionality is created and used during the design phase to define tolerances and locator/clamp positions, based on assumed variation, and is now inherited and used during production to fine-tune and adjust the process to the real geometry of incoming parts. The Digital Twin has an interface to the inspection database that contains information about individual part geometries as well as statistical distributions for batches of parts. The concept of the self-compensating assembly line is built up by the following steps (see also Fig. 4):

1. Individual parts A and B are scanned and data are stored as deviations from nominal in all nodes of the meshes.
2. Parts are sorted in classes to allow for pairwise matching.
3. Based on scan data for part A and part B, pairwise matching is conducted. The matching criteria is to minimize deviation from nominal after welding.
4. Based on scan data for part A and part B, deviation after joining is further minimized by adjusting the fixture elements (locating schemes for the two parts).
5. Based on scan data for part A and part B, the optimal welding sequence is selected – also here the goal is to minimize deviation after welding.
6. Subassembly A/B is inspected and compared to simulated geometry (including steps 2–4). Deviations between simulated and inspected geometry is related to fixtures and locators using Root Cause Analysis (AI and machine learning can also be used for capturing non-modeled effects).

Adjustments in the process, to compensate for part deviations, can be made with respect to statistical parameters (mean value and standard deviation) to optimize the process batch wise, or for individuals. The latter assumes very fast scanning and optimization routines for optimizing locator positions and welding sequence which is a research challenge in itself. Due to need for calculation speed, minimizing the gap between the flanges to be welded may be a strategy to reduce deviation. Rapid deployment of remote laser welding to secure the quality of the weld joint was reported in [27].

6. Conclusion and discussion

A highly automated assembly line is a huge investment. Return on investment requires high product quality, factory throughput, equipment utilization, and flexibility as well as low energy consumption. Today, geometry related problems, resulting in late changes and delays usually constitute a significant part of the total cost for poor quality.

Therefore, a Digital Twin for geometry assurance is proposed. The Digital Twin contains geometry representation of the assembly, kinematic relations, FEA functionality, Monte Carlo simulation, material properties and link to inspection data base. The Digital Twin is created and used in the design phase to develop robust products and to distribute tolerances, but also inherited later on in the production phase to serve as a real-time controller for the assembly system. In the production phase the Digital Twin is fed with scan data from the part geometries and uses this to match parts, to adjust locator and clamp positions and to select the optimal joining sequence (see Fig. 5).

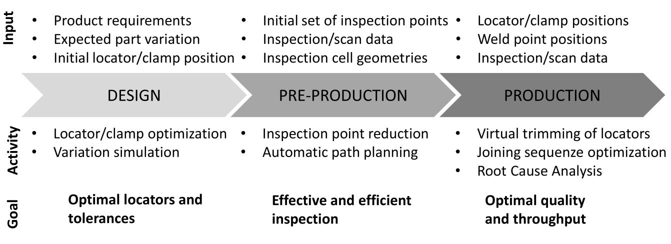

Fig. 5. Digital Twin input and functionality.

The Digital Twin can use data from individuals to perform real-time in-line individual adjustments or data from batches of parts to make adjustment batch wise. However, individual adjustment means new challenges related to scan speed as well as on simulation and analysis speed inside the Digital Twin.

An example with a sheet metal assembly station is given but the concept can be translated to any similar assembly situation.

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