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Digital Twinning in Additive Manufacturing – Closing the digital-physical-digital loop by automated integration of captured geometric data into fabrication information models

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Abstract. As part of the digitization of the AEC industry, the Digital Twin concept is becoming increasingly important. Originating in the manufacturing industry, the concept at its core involves a bidirectional coupling of the physical product and its digital counterpart with the aim of keeping the two in sync. Without appropriate capabilities to realize such synchronization, the concept always remained as an unattainable vision for the AEC industry. Adapting additive manufacturing (AM) for construction, however, creates unique opportunities to realize this vision by enabling automation in both directions, from digital to physical product and vice versa. As a fully automatable manufacturing method where robotic processes are typically controlled by the digital representation of the product, AM realizes the digital-to-physical link for this purpose. Conversely, based on the same digital representation of the product, the acquisition of the physical implementation of the manufacturing process can be automated, enabling the physical-to-digital connection. This paper uses three AM application scenarios to illustrate, on the one hand, the need for automating quality control and, on the other hand, to describe approaches for its realization. In particular, the benefits of synergy between automated quality control (QC) and fabrication information modeling (FIM) to form a digital-physical-digital loop are explored.

Keywords: FIM · Digital Twin · Cyber Physical Systems · Automated Inspection

1 Introduction

The concept of Digital Twin — originating from the manufacturing industry and increasingly being adopted in the AEC industry — comprises in its core a bidirectional coupling of the physical product and its digital replica with the goal of keeping both in sync [3]. Applying additive manufacturing in construction provides the unique opportunity for realizing the full Digital Twin vision by enabling automation in both directions, from the digital to physical and vice versa. As additive manufacturing is typically realized by means of robotic processes that are steered by the digital representation of the product, the digital-to-physical link can be directly implemented. The physical-digital link, on the other hand, can be realized by capturing the physical realization of the printing process and subsequently updating the digital twin.

In this paper, we report on both parts of the bidirectional linking between the digital and the physical twin: For the digital-to-physical part, we present Fabrication Information Models as a digital representation comprising all information necessary for driving the fabrication process in additive manufacturing. We discuss FIM as a means for interlinking building models with detailed manufacturing information such as printing paths, extrusion rates and material compositions. While a FIM abstracts from specific machinery and control languages, it can be utilized directly for robot control by automatic translation processes.

A well-known challenge of additive manufacturing with concrete and similar materials is the deviation of as-built component from as-designed model that necessitate thorough quality control (QC). While larger deviations are typically interpreted as a failed print, minor deviations are usually tolerated. Especially in these cases, it is of utmost importance to update the digital representation to allow consideration of the real geometry in downstream workflows, for example in assembly processes. This update of the digital representation procedure closes the digital loop and realizes the concept of digital twinning.

In this paper we describe in detail which information is needed and discuss a possible way to establish information exchange from the as-printed object (physical object) to the FIM model (digital object). This exchange of information is categorized by three scenarios from shotcrete 3D printing with an illustrative example for each case. These scenarios are defined based on various QC aspects during and after the fabrication process.

The first scenario concerns the status of the object before the surface finishing and edge trimming step where the object is still in its rough state. In this scenario, the QC consists of point-wise deviation analysis of the as-built point cloud to as-designed model as well as layer-wise inspection. The second scenario deals with the printed object after the surface finishing and edge trimming where the manufacturing process is finished. Thus, QC in this scenario can be executed by extracting geometric features such as boundaries, surfaces which are to be used for comparison and updating the corresponding information in FIM. The third scenario focuses on the assembly of different components using special joint features and thus on the mutual coordination of several components with each other. The third scenario focuses on the assembly of different components using special joint features and thus on the mutual coordination of several components with each other. In this case, QC takes on several tasks at once. On the one hand, the first component must be measured at the joint with an increased level of detail, and on the other hand, it must be ensured that the recorded joint geometry is transferred to the other component with an appropriate margin of tolerance.

In this context, we discuss the variety of digital representations necessary for closing the Digital Twin loop, involving process, volume and surface descriptions on different spatial and temporal scales.

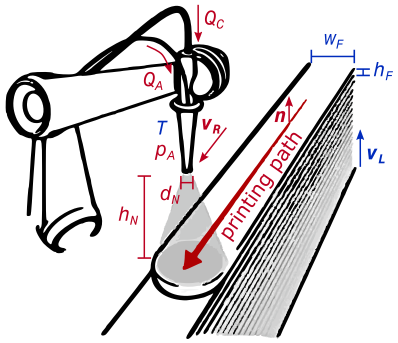
2 Background

2.1 Shotcrete 3D Printing (SC3DP)

The Shotcrete 3D Printing (SC3DP) process represents an Additive Manufacturing (AM) method developed by Lindemann et al [15]. In this method, the shotcrete process, which has long been used in tunnel construction, is fully automated by means of robotic guidance (cf. fig. 1). As in the established shotcrete process, the concrete is pumped to the nozzle via a hose, accelerated from there by a stream of air and sprayed onto the intended area.

Comparable to AM methods, the shape and quantity of the sprayed concrete filament in the SC3DP process is adjusted by several parameters (see fig. 1, right) [12]. However, with SC3DP, the form-defining AM parameters (filament width, w_F and layer height, h_F) have to be adjusted indirectly. The farther the spray cone of the AM system is above a certain position, the more material is applied there, and the further away the nozzle is from the point of application, the larger the base area of the spray cone. Therefore, the filament height can be set via the movement speed and the filament width via the nozzle distance [12].

In general, however, it should be noted that the other parameters mentioned in fig. 1 can also have an influence on the height and width. Therefore, for a successful application of this AM method, a precise coordination of the involved parameters is necessary, which makes the planning of the robot control significantly more complex and errors can occur more easily during the execution. If, for example, the planned layer height is not reached while applying one layer,



Independent/Set parameters
d_N: Nozzle diameter *[mm]*
h_N: Nozzle distance *[mm]*
Q_C: Volume flow, concrete *[m^3/h]*
Q_A: Volume flow, air *[m^3/h]*
p_A: Air pressure at nozzle *[bar]*
$\mathbf{v_R}$: Robot speed *[mm/min]*
$\mathbf{n}$: Normal vector on layer *[-]*

Dependent/Derived parameters
w_F: Filament width *[mm]*
h_F: Filament height *[mm]*
$\mathbf{v_L}$: Layer speed *[1/min]*
T : Robot tool frame

Fig. 1: Shotcrete 3D Printing (SC3DP) method with a selection of important parameters, after [12].

this also has a consequential effect on the next layer [14]. For this reason, it is essential to use automated control systems for SC3DP in order to use this technology more reliably.

In turn, the SC3DP process offers many advantages that can be used to solve various problems in the application of AM. Among other things, this method makes it possible to integrate reinforcement in the component [9], allows to apply material directly on already existing geometries and enables a very high geometric freedom. Although SC3DP is a very coarse process that cannot produce detailed features, it can be used to print very fast and, depending on the concrete mix, the still-soft concrete can be easily detailed with finishing steps such as trimming and smoothing [15].

2.2 Fabrication Information Modeling

The term *Fabrication Information Modeling (FIM)* was introduced by Duro-Royo and Oxman [7] as "[. . .] a methodology designed to bridge the gap between virtual design tools and advanced digital fabrication tools". Based on this definition, Slepicka et al. [21] developed a FIM framework specifically for the construction industry that enables the use of AM methods driven by BIM data. With the help of the FIM framework, it is possible to component-wise extract BIM data in order to subsequently enrich it with all the information relevant for automated manufacturing. The framework is designed in such a way that the manufacturing information created is as universally valid as possible in order to be able to use this data with different manufacturing robots.

Figure 2 depicts the interaction of BIM, FIM and the manufacturing machine schematically. As clearly illustrated, FIM represents an intermediate layer between digital design and digital manufacturing. In addition, FIM can be used for

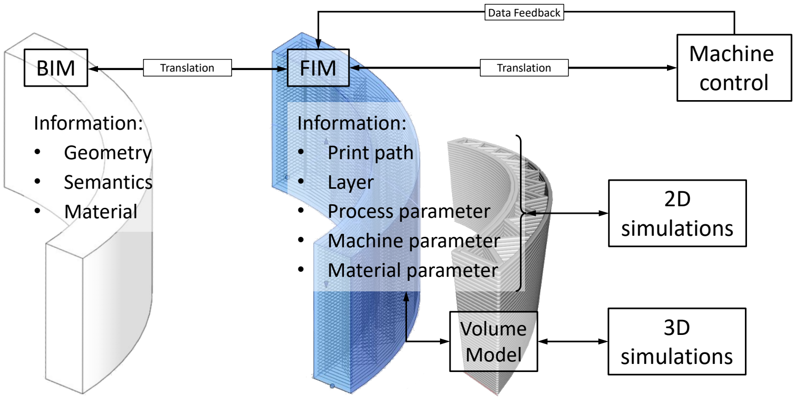


Fig. 2: From Digital Design to Manufacturing with Fabrication Information Modeling [21].

many other use cases via appropriate interfaces. Among other things, the data can be converted directly into a simulation model that can be used to predict various properties (e.g., thermal transmittance, structural integrity, and others) of the component [1].

Using the BIM data as a basis, the geometry of a component is further refined in the FIM model so that its internal structure can be tailored according to the given boundary conditions. Functional internals that were designed in the BIM model can be taken into account directly, so that many post-processing steps can be bypassed. In addition, information on the process flow can be designed in parallel to the fabrication information in order to predict material consumption and operating times.

In FIM, the outer geometry of the component is taken from the BIM model and, if not already designed in this way, converted into a Boundary Representation (B-Rep). Then the printing layers required for the process are modeled as separate entities to which the corresponding surface geometry (layer surface) is assigned. As the next step, the printing path is created for each layer in the parameter space of the layer surface and represented as a composite curve consisting of line, arc and/or spline segments. Finally, the relevant machine-, material- and process parameters are chosen or derived from the components geometry (cf. section 2.1). Since the component geometry is specified from the digital design, defining filament width and height, a number of independent control variables must be inversely determined for the SC3DP process.

The B-Rep of the component in FIM not only represents the BIM geometry, but can also be understood as a bounding box within which all the printed material is to be located. By definition the layer surface corresponds to the upper surface of a printing layer and can be considered as a reference surface for the nozzle positioning and later for sensor data ("as-designed" to "as-printed" comparison). The printing path describes the center axis of the printing filaments upper surface (cf. fig. 1) and thus represents an abstraction of the components expected print geometry. As stated in the previous section, the printing nozzle of a SC3DP machine has to be guided at a distance (h_N) normal ($\boldsymbol{n}$) to the respective layer surface (cf. section 2.1 and fig. 1). If the geometric information (path and layer surface) is planned in the robot's base coordinate system, the machine control can be derived directly, taking into account the selected process parameters.

2.3 Digital Twinning in Construction and Cyber Physical Systems

There are various conceptual descriptions for the term digital twin (DT), which in the original sense are based on the same core statement: A DT represents a digital image of a real object (or process) that already exists or will exist in the future, which is regularly updated to reflect the current state of the object (or process) (see literature review of Kitzinger et al. [13]). The DT representation must be available in an abstraction that is reasonable for the respective purpose but at the same time in a sufficient level of detail. One of the main purposes of a DT is to provide a comprehensive data basis for simulation, optimization and other planning tasks in order to make production, use, maintenance as well as demolition more efficient and sustainable [20].

However, one important component is missing if this concept is to be applied, namely how the processes involved in data exchange are linked to each other. A true digital twin can only be realized if its digital and physical sides are synchronized with every modification (no matter on which side) [13]. Thus, any modification to the physical side must be captured and transferred to the digital side, or conversely, any design change on the digital side must also be executed in reality.

Cyber-physical systems (CPS) are the underlying concept for realizing the circular flow of information just described. CPS are defined as "complex systems with organic integration and in-depth collaboration of computation, communications and control (3C) technology" [16]. In this sense, a CPS is a conjunction of technologies with which digital and physical part of a DT are linked. On the one hand, reality can be automatically captured and digitized and, on the other hand, conclusions can be automatically drawn from real events, enabling designs and the corresponding processes for their realization to be adapted. A decisive characteristic of CPS is that all information must be available on the respective side so that the system can be used throughout all phases of the life cycle of the corresponding object [10].

To enable this concept for AM in construction, mechanisms and algorithms for networking manufacturing processes (digital to physical) with sensor processes (physical to digital) must be developed, as shown in fig. 3. For this purpose, both an automated derivation of information from the sensor feedback and

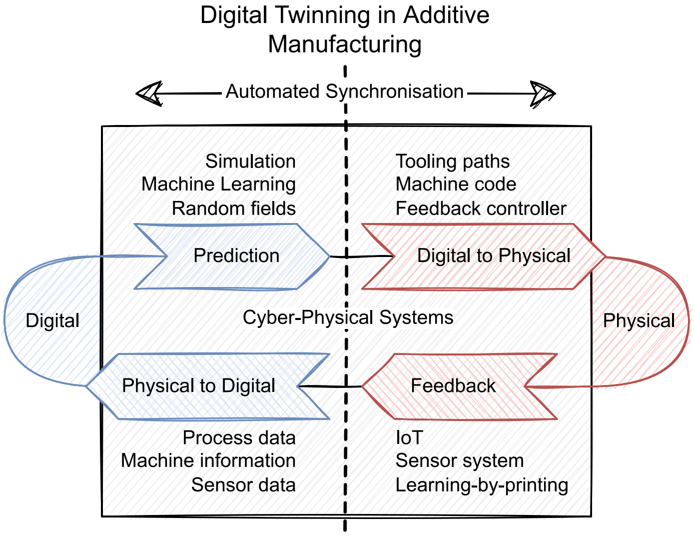


Fig. 3: Visualization of the circular flow of information during synchronization of the digital and physical sides of a digital twin.

a direct implementation of the feedback control by interpretation of this information must be realized. In other words, an integration of synchronized quality control (cf. section 2.4) into the design and manufacturing process (FIM) is necessary.

2.4 Quality Control for Additive Manufacturing

There is a lack of knowledge regarding the accuracy of concrete printing processes, as well as how they compare with each other [5]. As part of the digital fabrication process, a variety of stages are involved in the printing of an object [8]. As a result, quality control should be implemented both during and after each stage of the process. In this context, Kim et al. [11] investigate the current research on QC with different sensors. They point out that geometric defects may occur on concrete elements and that these defects can be detected before assembly.

Quality Control can be classified based on its application in the process, to *online*, *stage-wise* or *pre-assembly* (after surface finishing) control, and *assembly verification* [18]. In general, data is collected for each manufacturing step, from which features and attributes are extracted to provide meaningful information. However, different applications require different parameter settings and impose different boundary conditions. In section 4 the different QC classes are illustrated on the basis of different scenarios.

While online control acquires sensor data in a continuous stream and is typically used to monitor process parameters, such as the nozzle distance (h_N, fig. 1) [14], the other QC types are applied discontinuously at specific checkpoints. Stage-wise control of the printed object (referred to in [18] as layer-wise quality control) is performed at predefined epochs during manufacturing. Its main purpose is to ensure compliance with the requirements for the subsequent stages or processes and to capture the geometry at the end of the respective manufacturing stage for later use (production history). During stage-wise control two main checks are performed: Point-wise inspection and feature-wise inspection. These two inspection steps require the captured data to be aligned with their digital twin. As a reference for stage control, the FIM model provides the “as-designed” information of the component in the form of a B-Rep and the respective layer surfaces as NURBS-surface (cf. section 2.2).

The pre-assembly control deals with extracting more specific features, such as edges and semantic information of the surface, after any post-processing stages. In contrast to stage control, the pre-assembly QC requires no alignment between the object and its digital model [18]. Finally, assembly verification is used to confirm that the component is assembled correctly.

The results from any kind of inspection must always be reported back to the FIM to update the model accordingly.

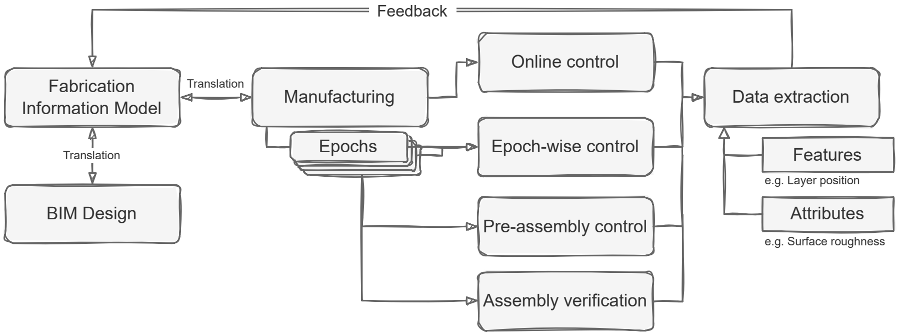


Fig. 4: FIM-Framework (cf. fig. 2) with extensions for automated quality control.

3 Methodology

As described in section 2.2, FIM can be used as an intermediate layer to enable a link between digital design and digital manufacturing. Although this link allows manufacturing planning processes to be integrated with digital design and data exchange to be consolidated, this alone does not enable full automation of the manufacturing process. To achieve this, tools for the integration and automation of quality control (cf. section 2.4) must be incorporated into the FIM framework to close the digital-physical-digital loop. This extension will evolve FIM into a cyber-physical system.

Figure 4 shows the necessary FIM extensions in the form of a flowchart, namely *online*, *stage* and *pre-assembly* control as well as *assembly verification*. In addition to the translation mechanisms already implemented in the FIM framework, tools for planning and evaluating scanning processes are being developed. The objective here is that the component being manufactured can be scanned completely and in high quality, either continuously during the printing process (online control), discontinuously at specific checkpoints in the manufacturing process (stage and pre-assembly control) or once after manufacturing and placement (verification), as described in section 2.4. From the collected scan data, it is intended that features can then be automatically recognized and checked against the “as-designed” model. Perceived deviations from the “as-designed” model should then either be automatically corrected by feedback or annotated accordingly in the FIM model.

FIM provides, as described in section 2.2, not only the manufacturing recipe but also a list of geometric representations of the object that can be utilized by the QC processes and be enriched by the feedback. Knowing where material is to be applied can help plan ahead for optimal scanner positioning, and measuring where material is actually placed can help guide future manufacturing steps. Integrating the different QC types, described in section 2.4, into the FIM framework will form a link between the digital and physical world and thus completes a digital-physical-digital loop.

In the experimental application (cf. section 4), three selected scenarios are described to emphasise the importance of the combination of FIM and QC for different geometric shapes and different fabrication stages. The quality control in this study is mainly focused on geometric data acquisition and here mainly on terrestrial laser scanning (TLS). Other methods are, of course, applicable, but require a more detailed evaluation of the particular sensor capabilities and limitations, as well as the impact of the respective quantity being measured on the process.

4 Experimental application

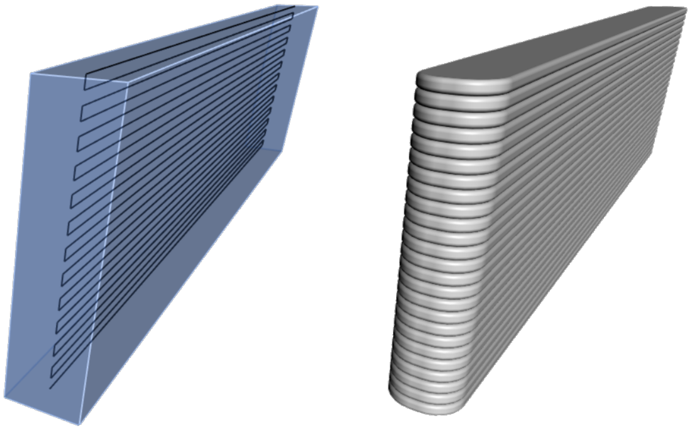
In the following, three scenarios are used to illustrate possible use cases for automated quality control (QC) and at the same time discuss the corresponding problems. For all three scenarios, it will be explained how the production data is generated and which properties of the respective component are to be monitored. In all scenarios, the shotcrete printing method (SC3DP) is used as the fabrication method. Since simplified examples are shown in the scenarios, it is not necessary to consider the component semantics; only the geometric information is required for the FIM in this case.

4.1 Scenario 1: Simple straight concrete wall

In scenario 1, the manufacturing process of a simple straight wall, with dimensions 1.6 m × 0.12 m × 0.45 m (length × width × height), is to be monitored [14]. The wall is to be built in a single-stage manufacturing process and is not to be post-processed afterwards. The objective in this example is to monitor whether the printed material is within the planned boundary surfaces and to detect the exact location of each printing layer.

FIM: In order to generate the FIM model for this example, the geometry is first imported and translated into a B-Rep model as described in section 2.2. After that, the B-Rep is horizontally sliced into the individual layer surfaces at 15 mm intervals (layer height h_L), between which the material is applied. In FIM each layer is defined to be one base step. The subsequent path planning is done by fitting a printable filament onto each layer, which is done in this simple example simply by finding the center-line of the layer surface. To complete the robot motion all layers are connected with vertical lines, which represent the layer transitions.

As shown in fig. 5a, the printing path in this example consists of a straight horizontal line in each layer, along which material is applied, and the vertical layer transition, along which no material is deposited. Based on this, a prediction can be made about the printed filaments by sweeping an estimated cross-section along the horizontal curves of the path (cf. fig. 5b).



(a) B-Rep and planned printing path of the simple straight wall.

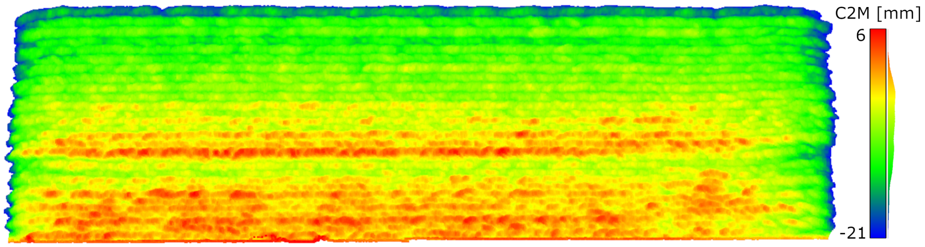
(b) Expected print result

Fig. 5: Digital model (FIM) of the simple straight concrete wall.

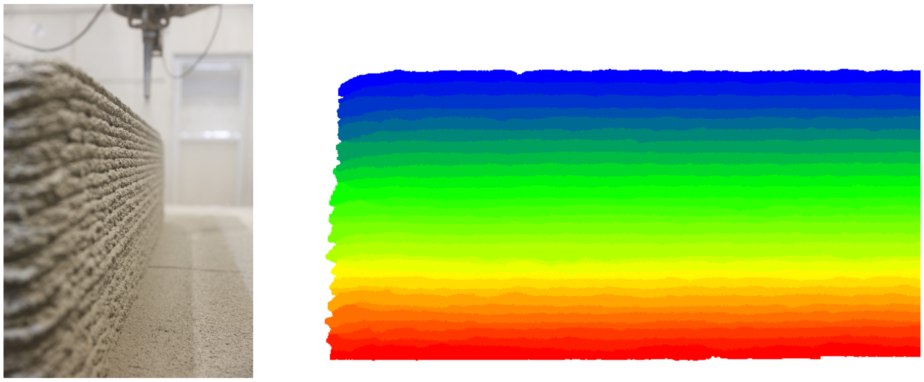
QC: As mentioned before the wall in this example was not planned to be post-processed (see fig. 6b) and only online and stage control were applied (cf. section 2.4). The online control of this example was discussed in detail by Lachmayer et al. [14]. A tool-mounted laser profiler that measures the relative position of the robot tool to the top surface of the partially printed wall segment is used for a fine-grained control of the nozzle distance (see also section 2.1). For the stage control illustrated in fig. 6, a TLS mounted on a separate robot is used to capture the components geometry and position. By direct co-registration with the digital model and applying cloud to mesh (C2M) (or alternatively M3C2) algorithms [18], the deviation map (see fig. 6a) is extracted, providing the deviation distance for every captured point (deviation map). In order to analyze the process in more detail, a manual segmentation into the individual layers is carried out as shwon in fig. 6c.

Analysis: As shown in Fig. 6, the finished component looks similar to its digital model (cf. fig. 5), but differs in certain details. The most important deviations include the fact that the designed height is not met, the sides are realized rather inaccurately and the planned width is exceeded in many places (cf. fig. 6a). In addition, the segmented point cloud (fig. 6c) shows flaws on the level of individual layers. However, all of these results were created manually, long after the process was complete. Integrating quality control into FIM could not only automate the evaluation of measurements, but also initiate processes to counteract the previously mentioned problems.

If the recorded geometry is compared with the digital model, it can be checked whether the component meets the requirements for the next production stage or



(a) C2M distance between the point cloud and digital model.



(b) "As-manufactured" (c) Manually labeled point cloud data.

Fig. 6: "As-manufactured" data for the simple Wall [6, 14].

whether further steps are necessary. In case of the shown example, the reached height was 429.77 mm and therefore additional 1.35 layers would need to be printed to reach the planned 450 mm. With FIM, this can be automated and the process could be extended directly, saving these changes directly in the model, needless to say.

The labeled data shown in fig. 6c was tediously created by hand, which was time-consuming and error-prone due to the fuzzy edges, and as a result still does not fully represent reality, as only 29 layers were counted (there should be 30). By automating the labeling process, this process could be performed much faster and less error-prone, while at the same time extracting the surface of the "as-manufactured" layer. The extracted layer surfaces could then be used to update the digital model and possibly utilized in advanced FEM analyses. It is worth noting that point-wise inspection can be used as a basis for the segmentation process (filament detection), as it provides a deviation map of the created object from its digital model. However, the sensor type, data quality as well as the filament feature detection methodology determines the quality of the segmentation process. Furthermore, another challenge corresponding to the filament detection is the differentiation process that detects the individual layers, as the filament borders may not always be separated clearly.

The heat map shown in fig. 6a contains information about the surface quality of the simple wall example. As shown, the deviations are in the range of -2.1 cm to 0.6 cm, which might necessitate post-processing, such as surface smoothing, depending on the required tolerances of the object. Although not applied here, the dense geometric map of the rough surface can be used to create the machine control code for the smoothing motion. Even if the measurement data is processed directly, it may still be useful later, e.g. when used for predictions in similar projects. However, the amount of data collected using TLS is quite substantial, so abstraction of the data to an appropriate level must be considered. The point-wise inspection results, for example, can be approximated into pixel-based deviation maps that can be reported back to the FIM and applied to the B-Rep of the component. Another option would be to replace the point cloud data with a B-spline approximation, which not only increases data efficiency but also removes noise [19].

4.2 Scenario 2: Double curved reinforced concrete wall

For the second scenario, the real-size demonstrator [9] is used as example. This demonstrator is a double-curved reinforced wall that was built in several manufacturing stages and finally post-processed for a smooth surface (cf. fig. 7).

Noteworthy features of the demonstrator are, first, the geometric complexity and, second, the multi-scale details in the centimeter and meter range. Similar to the first scenario (section 4.1), stage control was performed, but is not discussed in detail here to avoid repetition. More important for this scenario is pre-assembly control, which was performed after the edge trimming and surface finishing steps (cf. section 2.1). After the post-processing, the object is expected to have a defined shape close to the designed model.

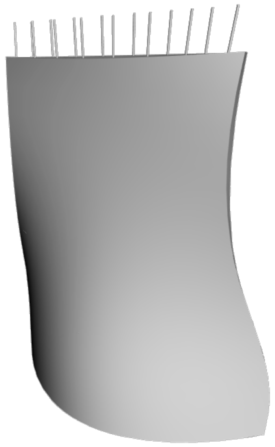
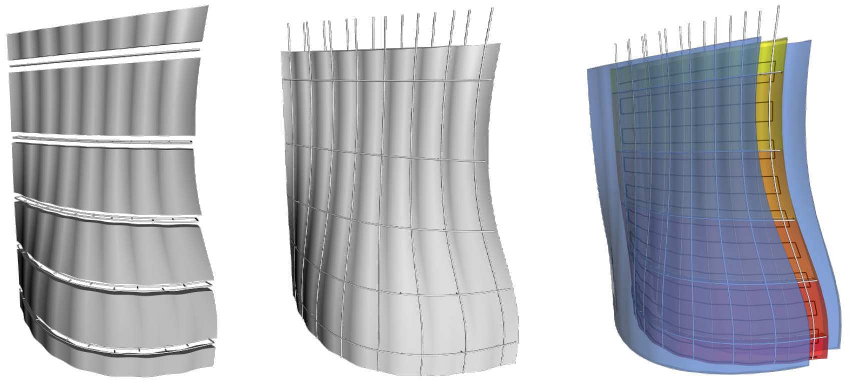


Fig. 7: Digital model of the double curved reinforced concrete wall example [9].

FIM: The manufacturing process of the shown example is, as previously stated, separated into different printing stages to enable the insertion of rebars. The following description is a slightly modified revision of Hack and Kloft's process description [9] in the context of FIM. As the first set of stages, the core structure is printed layer by layer, which is designed to contain pockets for the placement of reinforcement. At the end of each core structure stage (except the last), a horizontal layer of reinforcement is placed. Once the core structure is finished, the vertical rebars are added in the second stage and covered with the surface coating immediately afterwards in the third stage. Finally, in the last stage, the surface is post-processed using different sized rotating discs in three smoothing steps.

Each of the steps described above is represented in FIM as list of base steps, similar to the first scenario (cf. section 4.1). First, the core structure is sliced into individual printing layers, each representing a base step and for each of which the printing instructions are generated (layer instruction). In addition, the placement of horizontal reinforcing bars is scheduled after a certain number of layers. Since each placement of horizontal rebars disrupts the printing process and the correct position of the rebars must be ensured, the production of the core structure is divided into further sub-stages, one sub-stage per rebar layer and per concrete segment (cf. fig. 8a). Next, the vertical rebar placement is split into each individual placement step and grouped as the second stage (cf. fig. 8b).

After that, the surface coating processes are designed similarly to the first stage and grouped as the third stage. Path planning is performed in this stage in the respective parameter space of the designed smooth faces of the component (finished state, fig. 7). However, the substrate in this process corresponds to the

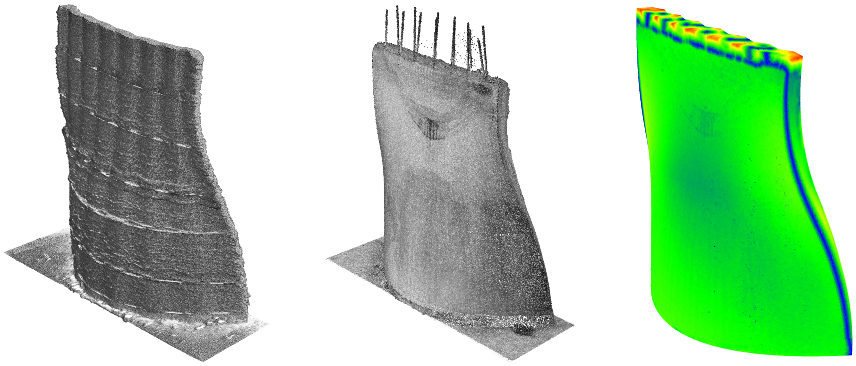


(a) Stage 1a–k: Core structure including horizontal rebars.

(b) Stage 2: Vertical rebar placement.

(c) Stage 3 & 4: Surface coating and finishing.

Fig. 8: Geometric representation of the different manufacturing stages for the double curved wall demonstrator [9]. Figures 8a and 8c are shown as an exploded view for clarity.


(a) Intermediate manufacturing stage.

(b) Laser scan of the finished wall.

(c) Deviation map.

Fig. 9: Laser scan data taken during the manufacturing of the double curved wall example [9] and processed deviation map [4].

respective side surface of the core structure, all of which are uneven, which is why the layer height is not constant. Finally, all smoothing steps are combined as the 4th and last stage (cf. fig. 8c).

Each (sub-)stage therefore represents a set of individual base steps, that can be executed in direct succession (continuous group). A continuous group can be manufactured without changing the robot tool, and QC can take place between each of these groups.

QC: This scenario is in many ways more complex than the previous case study, as it involves multi-stage manufacturing of a concrete and steel component including subtractive surface finishing. Each stage has been controlled using online and stage control and the finished wall was inspected with pre-assembly control [4]. As in the previous scenario, the online control was used to monitor the nozzle distance and thus stabilize the process. For the surface coating process before the final smoothing, stage control was used to generate a design basis (cf. fig. 9a). Using the scan data a printing path was generated for the material application covering the installed rebars. The pre-assembly control at the end was performed to record the "as-manufactured" condition of the component after the surface finishing (cf. fig. 9b) and compared with the digital model utilizing C2M algorithms (cf. fig. 9c).

Analysis: Compared to the first scenario, the final product in this scenario displays much less deviation from the digital model (cf. fig. 9c). It was possible to compensate for process- and material-related deviations by means of surface processing, so that deviations of less than 10 mm could be achieved [9]. However, some steps were carried out manually during the manufacturing process and the measurement data were evaluated using individually developed scripts.

Online and stage control was largely analogous to scenario 1. However, stage control could have been particularly useful in the first stage (cf. fig. 8a) to ensure that the individual core segments (partial stages) were produced accurately and that the horizontal reinforcing bars were placed in the correct position (with the "as-built" position also being recorded). The same applies to the vertical rebars in the second stage (cf. fig. 8b). The third stage (cf. fig. 8c) was based solely on the measurement data from stage control.

Also in this example, automating the QC would speed up the process and more of the fabrication process could have been automated, such as the placement of reinforcement. However, the sensor selection for feature extraction and object detection in the stage control of this example needs further investigation. The previously mentioned detection of rebar is a difficult task for laser scanners because the signals received from the metals have a high reflectivity. In addition, the small shape of the rebars may result in a point cloud of poor quality due to noise.

The pre-assembly control in this example deals with extracting features from the printed object and comparing them with their digital counterpart [17]. The advantage of this inspection method is that the two data sets (digital and physical) do not have to be aligned because the object features can be compared directly. This feature eliminates the error factors associated with the alignment step. Any detected feature, such as boundary edges or surfaces, can be fed back into the FIM model as NURBS curves or surfaces. In addition to features, attributes such as flatness, smoothness, roughness, and others can be tested during pre-assembly inspection and fed back to FIM by annotation of the respective geometric element.

In general, the inspection cycles and feedback workflow enable increased automation of production. By using FIM as a central data repository, all collected measurement data can be accessed easily and efficiently. If there is a direct data feedback, a model can be adjusted in real time and in turn influence the production, i.e. a CPS can be realized (cf. section 2.3).

4.3 Scenario 3: Key and Lock joint features

This example shows the manufacturing of a key and lock joint feature (cf. fig. 10) that are to be assembled. FIM is not yet extended to represent such features, but conceptually these features can also be manufactured in a similar way as described in the previous scenarios.

FIM: Since a FIM model represents a single component, connection features, as shown in this example, act as an interface between different FIM models. Thus, one FIM model contains the key feature and another FIM model contains the fitting lock feature. This introduces the difficulty that the corresponding geometry must be designed across components.

The third scenario shows again components that have to be created in more than one manufacturing stage. Since the SC3DP process is not suitable for generating high-resolution geometries, an approximated shape must first be created,

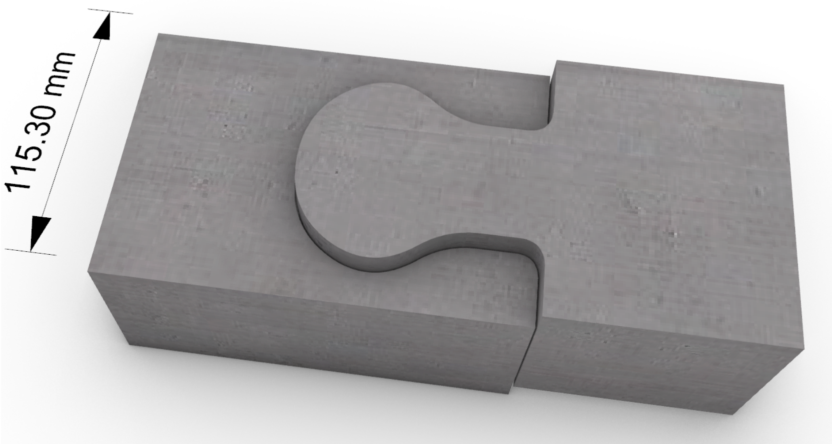


Fig. 10: Digital model of the Key and Lock joint [2]. It is meant to be a Demonstrator for a joining feature. Applied to a component the design may need to be resized.

which can be adapted to the planned geometry with high accuracy in a subtractive post-processing stage. Thereby, it is important to make sure that the AM geometry fully incorporates the planned feature in order to limit the number of post-processing steps required.

For both components the AM process must be planned with a sufficiently oversized geometry. In addition, the trim geometries for both components must be fitted consistently with each other so that this joint does not affect the absolute position of the components. This also means that very small manufacturing tolerances must be considered.

For this example, both sides were modeled as cuboids and a subtraction solid was created for each side. The subtraction solid for one side was planned freely and then used for the other side as a negative with some offset. For the complex geometry of the interface an extruded NURBS curve was defined.

QC: As in the previous scenarios, all the different types of quality control could be discussed in this scenario, but here the focus is on pre-assembly control section 2.4 and in particular focused on the joint feature. To this end, the most important task is to detect features such as edges and surfaces in high detail at the points where different components are to be joined. In this example, the omega-shaped area represents the interface and must be captured on both sides of the joint, i.e. measured separately for each component involved. An assembly of the components involved is only possible if both recorded surfaces can be arranged with sufficient distance to each other.

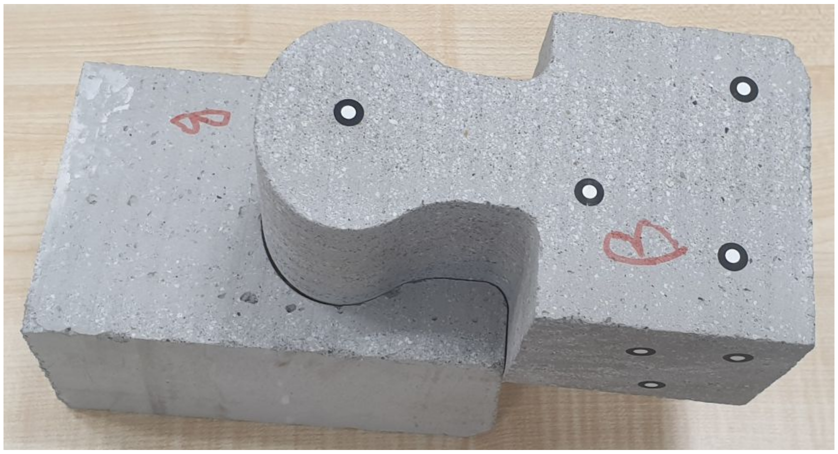


Fig. 11: 3D printed specimen [2].

Analysis: The two omega-shaped components were 3D printed just as in the previous examples. For the realization of the contact surface, material was removed accordingly after printing with a milling machine. In contrast to scenario 2, however, the material was not removed until the concrete had completely hardened. A difficulty in this example can be that the components have to be moved between the two manufacturing stages, so that the milling process has to be aligned with the repositioning of the components.

During the manufacture of components containing joints, the following errors, among others, can occur. On the one hand, the respective sides of the joint can be manufactured incorrectly so that they do not fit into each other. Secondly, the position of the joint may be incorrectly arranged on the component so that it fits together with its respective counterpart, but is then incorrectly positioned in a global sense.

The assembly shown in fig. 11 exhibits the first of the two errors mentioned; although the components appear to be correct, they will not mate.

It can therefore be said that components containing joints require a very high degree of precision during manufacture, which makes a corresponding quality control absolutely essential. However, it can be problematic here that the selected sensor, i.e. TLS, can record the geometry in a resolution within the tolerance range of the joint. In addition, joints can only make up a small part of the component, which is why the sensor must be able to measure more densely in these parts of the component.

5 Conclusion and Outlook

A frequently cited advantage of AM is that it is a fully automatable manufacturing method that could help increase productivity in the construction industry.

However, human supervision is still required for a meaningful use of this method according to the current state of the art. By itself and without appropriately programmed fail-safes, a robot will stubbornly execute its predefined program regardless of the outcome. It lacks the ability to detect, interpret and correct errors by itself.

In this study, different scenarios were investigated to determine the extent to which human supervision in the use of AM can be further reduced. For this purpose, we specifically investigated how automated QC can be implemented within FIM. In the scenarios it was shown that different types of QC are applicable depending on the process state and the desired component properties. Each demonstrated QC type has its own prerequisites, capabilities and requires a certain amount of preparation, such as the choice of sensor position (scan planning). In addition, for capturing certain materials and details in the required level of accuracy (LoA), sensor selection and settings must be optimized, e.g. when capturing the geometry of reflective metals. Thus, a good strategy for **sensor setup**, **information extraction** and **feedback** is crucial for QC automation.

As preparation, sensor examination and adjustment with regard to the requirements of the defined tolerances and the shape of the object is necessary to capture valuable data. In the case of TLS, parameters such as laser footprint, range, angle of incidence and material properties, can have a decisive influence on the quality of the corresponding data. Using FIM for the planning and execution of the AM process, all these parameters can be accessed at any time provided appropriate FIM extensions are made.

For the extraction of relevant information and the corresponding feedback, a distinction must be made depending on the QC type. In the case of online control discussed in section 4.1, a small local data set is processed immediately feeding back the obtained control value. The captured data (in the example a line profile) is obsolete at the latest after the next printing layer and does not need to be stored in FIM. During stage control, extracting information from the captured data involves direct co-registration of the captured data set with the geometric representation provided by FIM. The extracted point-wise information as well as the features are fed back to FIM to be used as a basis for planning the subsequent manufacturing stage. Finally, during pre-assembly control extracted features are extracted without co-registration and evaluated using FIM representations.

In addition, periodic inspection provides information on time-dependent effects during the manufacturing process, such as sagging and other changes in shape. Considering that the filament properties in the process are highly dependent on many different parameters such as material composition, nozzle spacing, nozzle diameter, extrusion speed, air pressure and robot speed, it is important to comprehensively document each manufacturing stage or sub-stage (cf. section 4.2). This alone allows a meaningful comparison to be made with the design information and conclusions to be drawn about parameter influences on the process in order to improve future projects.

Finally, it must be noted that automation of information extraction and feedback of QC results to FIM (digital part of DT) represents an update routine that always points to the current state of the real component (physical part of DT) and thus realizes the physical-digital connection (cf. section 2.3).

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