Digital Evaluation of Morphological and Visual Surface Characteristics of 3D-Printed Concrete

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Abstract –

This contribution presents the approach for the digital quality assessment of surfaces of additively manufactured concrete components. It is based on process-integrated sensor technology, surface-structural quality criteria, and integration into the cybernetic control loop of the printing process. A continuous target–actual comparison of the constructed geometry enables robotically adapted “first-time-right” processes and ensures a transparently defined standard in which the relevant quality criteria for contract, execution, and acceptance are clearly specified.

Keywords –

3-D concrete printing, quality assurance, surface characteristics, digital evaluation

1 Introduction

Concrete 3D printing has evolved from an experimental research technology into an increasingly industrially relevant construction method. Formwork-free, layer-wise extrusion opens up new structural and architectural degrees of freedom, reduces the need for manual labor, and enables a level of automation in structural construction processes that has not previously been achievable. At the same time, the paradigm of construction execution is shifting: whereas in conventional concrete construction the surface is the result of the interaction between fresh concrete and formwork, the surface of printed components is generated directly by the robotically controlled extrusion process. Process quality therefore becomes an integral component of surface quality.

Any local deviation from the optimal state in extrusion behaviour, rheological properties, or variations in the motion control of the print head manifests itself directly in the geometry and in the morphological–visual surface characteristics. These include filament-related criteria such as curvature, flatness, layer height, layer geometry, or texture, as well as component-related characteristics such as overall flatness, colour uniformity, or the geometry of wall connection regions. These features represent process-deterministic quality indicators and are therefore ideally suited for automated real-time control. In parallel, studies show that modern sensor technologies, ranging from camera systems and laser triangulation to ultrasonic or pressure sensing, are capable of capturing the state of material and structure during the printing process. This multimodal data basis constitutes the requirement for data-driven quality models, adaptive process control, and predictive corrections, which are essential for reliable robotic manufacturing systems. Against this background, this work aims to integrate classical surface quality criteria and sensor-based quality monitoring from concrete extrusion through to the completion stage into a robotics-centered, automated quality assurance model. In this context, the integration of a target–actual comparison of the constructed geometry represents a key element.

In concrete 3D printing the terms “layer” and “filament” are defined as follows. A filament refers to the continuous strand of concrete extruded from the nozzle along a defined print path. A filament represents the smallest printed unit. A layer, on the other hand, is a complete horizontal layer that may consist of several filaments lying side by side in a single plane. In solid wall printing, the layer corresponds to the filament, as the wall consists of only one filament. Several layers stacked on top of one another form the wall.

2 Transformation of the concept of exposed concrete surface characteristics

Conventional guidelines for exposed concrete, e.g., the DBV guideline “Sichtbeton” [industry guideline for exposed concrete surfaces], classify surfaces primarily based on the quality of formwork imprinting and the homogeneity of the cast concrete element. [1] However, key criteria, including e. g. texture, porosity, colour uniformity, and flatness, are only transferable to formwork-free additive manufacturing to a limited extent, since concrete 3D printing involves neither defined formwork surfaces nor continuous concreting sections. [2] Instead, the surface is generated layer by layer, with each layer being shaped by the interaction of extrusion, material consistency, and robotic motion. The representations shown in Figure 1 illustrate that printed filaments develop a specific morphology that is equally influenced by rheological properties, process-induced material deformations, and external effects. Consequently, the surface becomes a direct reflection of process quality - a fundamental distinction from conventional exposed concrete.

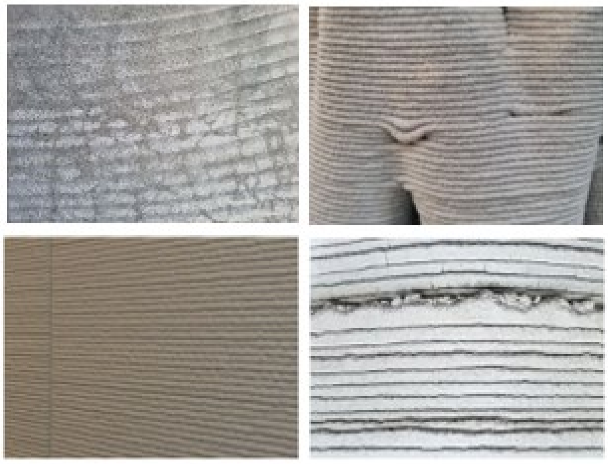

Figure 1: Examples of different wall qualities of 3-D-printed concrete components

2.1 Surface characteristics of the concrete 3D printing process

Since no formwork surface is present, the surface of printed concrete components is primarily formed by the layerwise material deposition, the robotic motion control, and the time dependent interaction of the filaments. In addition, the geometry and structure of the nozzle as well as the rheology of the material play a decisive role. Accordingly, surface characterization in concrete 3D printing must be carried out on multiple structural levels. This results in a two-stage model that distinguishes between filament related characteristics and component related surface characteristics. Overall, this system comprises 36 clearly definable properties that can be described within distinct geometric, morphological, and textural categories, as presented in the paper by Otto and Maiwald, *Classification and Automated Quality Assurance of 3D Concrete Printed Surfaces*.[3]

2.2 Filament related surface characteristics

Within the filament related level of observation, characteristics emerge that result directly from the extrusion process, corresponding to a control loop cycle within a single layer plane. These include in particular layer width and height, radii of curvature, cement paste tearing effects, surface roughness, local porosity, and edge formation characteristics as shown in Figure 2.

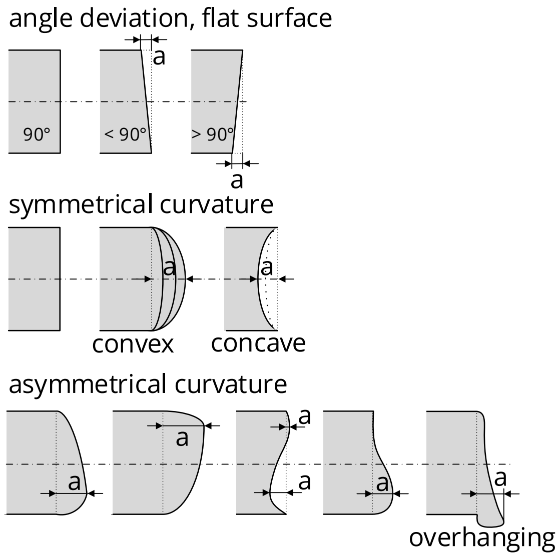

Figure 2: Excerpt from Variations in Layer Geometry [3]

The 36 uniquely defined filament indexed characteristics can be quantified, as reported in [3] primarily relating to the geometry of the component surface, texture, and colour uniformity. They are highly sensitive to process parameters such as nozzle geometry, extrusion volume flow rate, pump pressure, rotational speed of the screw conveyor, or external environmental conditions. Due to this direct process dependency, they are ideally suited for real time control of the printing system. Data from laser scanners, triangulation systems, as well as depth- and RGB cameras are processed immediately after filament deposition, compared with defined target values, and lead to immediate parameter adjustments such as an increase in the extrusion rate.[4]

2.3 Component related surface characteristics

At the second, global component level, layer and structure related characteristics emerge that arise only from the interaction of multiple filaments and combine to form the overall component. These include in particular horizontal layer offsets as shown in Figure 3, with typically permissible tolerances of a = 1–3 mm, non parallels, joint geometries, vertical deflections, settlements, and progressive curvature across multiple layers. This level comprises 11 characteristics that reflect both robotic precision and material behaviour over several minutes. [5]

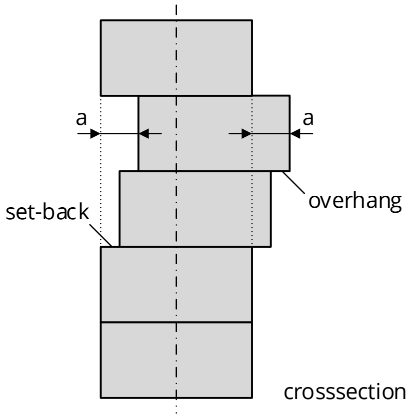

Figure 3: Representation of the global flatness of the additively manufactured concrete component [3]

3 Control loop-based integration of automated surface detection

The defined surface characteristics do not serve merely a descriptive function but constitute an integral part of the robotics centred quality control loop illustrated in Figure 4. Each group of characteristics fulfils a specific role within process accompanying monitoring as well as within the final quality assessment conducted as part of the acceptance procedure.

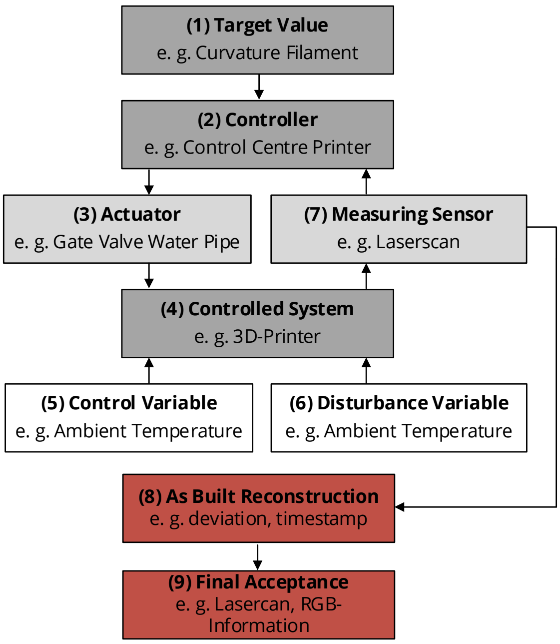

Figure 4: Extended 3D-concrete-printing control loop (adapted from Otto and Maiwald, 2024)

3.1 Extended Printing measurement data (7) in the control loop

The filament data captured by laser triangulation (Figure 5) as well as depth and RGB cameras serve as the initial basis for the emerging as built model (8) within the control loop. These data are used in the sense of a “first time right process,” allowing the component to be produced directly at the required quality level and minimizing the need for subsequent corrections. In this way, the control loop enables process integrated quality assurance, in which deviations are detected early and immediately compensated to achieve the target quality already in the first production cycle.

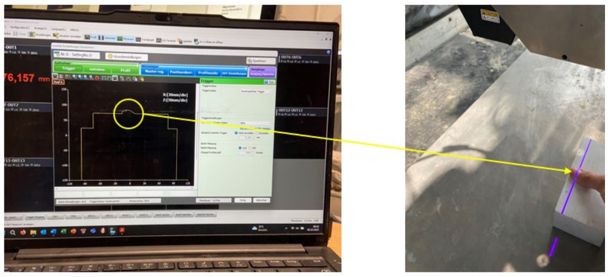

Figure 5: Laser triangulation system for detecting the layer geometry at the time of extrusion

Based on this data foundation, the subsequent processability of the additively manufactured component can already be assessed. [5] For example, if the typical tolerances of building construction, such as those specified in German Standard DIN 18202, are met, follow up trades such as drywall, plaster, or tiling can be carried out without restrictions. [7]

Within the control loop, the measurement data collected during the printing process (7) serve a bridging function: they are generated from the data captured for each filament but only become interpretable through appropriate aggregation, thereby significantly influencing the overall appearance across greater component height or width. At the same time, they are critical indicators of printing process induced changes, such as weather conditions, sudden viscosity fluctuations, or temperature induced material deformations.

3.2 Extended data capture for final acceptance

While filament and layer related data from the printing process are incorporated into the as built model (8), the component related exposed concrete surface quality requires additional measurements at the time of acceptance (9), for example through high resolution structure from motion recordings, component proximate laser scans, or colorimetric evaluations. Only the combination of process integrated data and final acceptance parameters provides a complete digital representation of the component, capturing geometric as well as morphological, visual, and colour properties. Typical characteristics include global flatness, wall curvature, right angle connections, colour uniformity, texture, crack features, and emergent surface formations that become visible only in the final state, for instance after hardening under site conditions.

3.3 Overall quality evaluation

The analysis of the control loop and the data derived from it shows that, in particular, geometric properties, cracks, and surface texture can already be captured sensorially during printing and integrated into the as built model. If only technical parameters are specified as contract requirements in a tender, condition oriented process monitoring is generally sufficient to ensure contract compliance. A separate final acceptance then does not require additional investigations. However, if visual properties, such as those required for exposed concrete are also contractually specified, supplementary automated measurement methods are necessary to evaluate them reliably.

4 Morphological and visual surface analysis

Since up to 36 geometric, morphological, and textural characteristic dimensions can be defined in concrete 3D printing, project and function specific selection of those characteristics that determine component relevant surface quality is required.

The large number of characteristics leads to a practically unlimited number of possible surface variations. Manual or purely visual assessment of these characteristics under real construction site conditions is neither reproducible nor objective, as subjective evaluations by personnel involved in the construction process can result in significant variability in judgment. In particular, for requirements that go beyond simple dimensional tolerances, such as exposed concrete like surfaces or geometrically complex transitions, consistency in evaluation can only be ensured through digital and automated measurement methods. The goal is therefore to generate a fully digital representation of the component surface and thus the real geometry. By integrating the captured data into the as built model, all filament related and component related characteristics can be systematically analysed, automatically compared with target values, and assessed with respect to compliance with contract specifications (Figure 6).

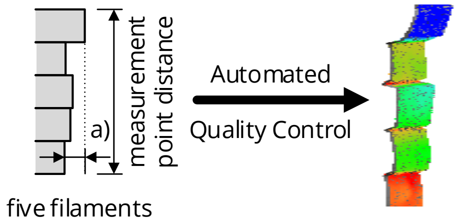

Figure 6: Representation of the automated target/actual comparison (adapted from Otto and Maiwald, 2024)

4.1 Methodology

With the transition from process accompanying monitoring to the acceptance procedure, the evaluation focus shifts from filament or layer indexed characteristics to component related surface parameters. The now fully cured material structure allows metrological capture of the final component geometry, enabling quantitative assessment of surface relevant quality parameters such as flatness, dimensional and shape accuracy, and colour uniformity.

To evaluate the method, digital and automated approaches for surface acquisition and analysis were employed. The evaluation was carried out automatically or semi automatically using self-developed software, complemented by the open-source software CloudCompare for processing, analysis, and visualization of 3D point clouds and meshes. The focus is on the fundamental performance of the methods for capturing printing specific surface characteristics as well as their practical applicability under typical construction site conditions.

The measurement devices investigated in this study are methodologically generalizable although implemented using specific equipment. The selected devices were chosen so that the systems' tolerance range matches the required tolerances of the application under investigation. This minimizes distortions caused by measurement uncertainties. In addition, references are made to the relevant literature, in which the fundamental capabilities and limitations of the measurement methods used for comparable applications have already been comprehensively evaluated and validated. [10, 11, 12, 13]

4.2 Experiment procedure

A test specimen consisted of a 50 × 50 cm surface produced using the full wall printing method. The layer height was h = 5 cm. [8] [9] The position, orientation, and reference points of the surface were kept constant across all experiments to ensure a comparable data basis. On this basis, a series of trials for digital surface acquisition were conducted, and the resulting geometric data were fed into the respective evaluation methods.

4.3 Manual laser line projection (MLP)

Manual laser line projection allows visual assessment of flatness deviations along a laser line projected at an angle. The principle is based on the structured light concept known from depth cameras, where a light pattern is projected onto the surface and depth information is derived from the pattern distortion. It converts the manual "Stichmaß" defined in German Standard DIN 18202, an established measure for flatness and dimensional tolerances in the construction industry, into a digitized tool. The results show that particularly larger offsets and pronounced layer deviations can be visually detected, while small scale deviations or subtle texture differences cannot be reliably captured metrologically. The laser does not generate a metric measurement signal but only an optical orientation line, which is captured using commercially available camera technology. The recorded RGB images, which serve among other purposes to assess colour uniformity, porosity, and surface structural characteristics, are supplemented with depth information via laser triangulation (Figure 7). This enables comprehensive coverage of both colour and geometry-based criteria. The developed software integrates these datasets, providing a readily deployable tool for localized, final surface quality assessment in accordance with the control loop (9).

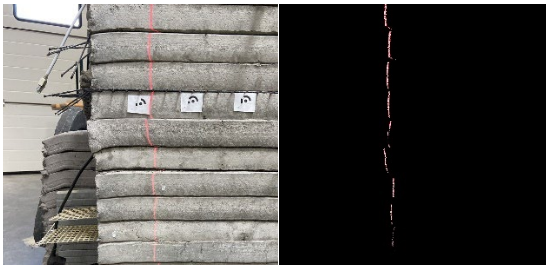

Figure 7: Manual laser line projection (left: RGB information, right: surface profile)

4.4 Tachymetry (TM)

Tachymetric point measurement using the Leica TS60 proved to be an extremely precise method for localized capture of layer geometry. [14] A major advantage is that most construction sites are already equipped with a tachymeter, so no additional investment is required. By defining measurement points per filament, vertical and horizontal offsets could be determined with high accuracy. This enables particularly quantitative assessment of layer placement, parallelism, and local flatness. However, the method has clear limitations regarding texture and fine scale surface characteristics, as point measurement does not provide continuous sampling of the filament surface. Furthermore, rough or highly curved filament surfaces complicate exact prism positioning (Figure 8), which limits reproducibility.

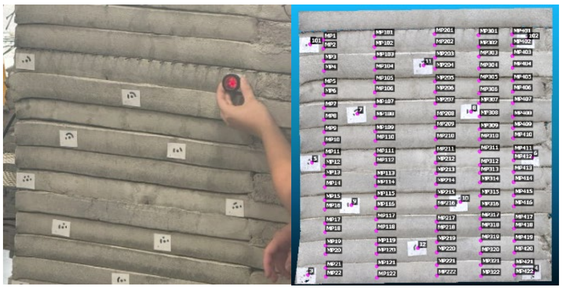

Figure 8: Tachymetric measurement of the component surface (TUD, Chair of Optical 3D-Metrology, 2025)

Overall, the tachymeter is primarily suitable for precise pointwise geometry capture but not for comprehensive surface characterization. In addition, no RGB data are recorded, preventing assessment of colour or texture properties.

4.5 Laserscan (LS)

A laser scanner captures surfaces by generating high resolution point clouds through active distance measurement, using either time of flight or phase comparison, from which the spatial geometry of a component can be reconstructed. The portable scanner used (Keyence WM 6000) inherently produces a high point density along the wall surface, making detailed geometric reproduction in principle possible. [15] However, several challenges arise in practical construction site implementation: conversion of proprietary data formats leads to scale deviations and inconsistent coordinate systems. Despite the high nominal point count, the point clouds also exhibited local noise and sparse points, which significantly complicates metric evaluation, particularly on curved or textured surfaces. In addition, no RGB information is captured (Figure 9).

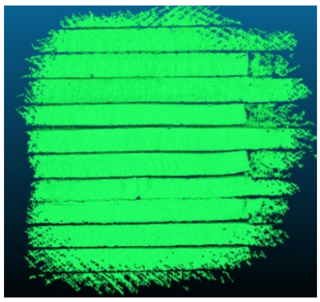

Figure 9: Representation (CloudCompare) of the component surface captured by laser scan (TUD, Chair of Optical 3D-Metrology, 2025)

While the method has high potential for precise area-based measurements, it requires robust data management and a consistent, compatible software workflow due to the large volume of generated data.

4.6 LiDAR (Li)

The LiDAR scanner used (Blickfeld Cube 1), due to its sensor geometry and focus on environmental perception, is only of limited suitability for component proximate surface acquisition. [16] The resulting point clouds were characterized by comparatively high noise (Figure 10) and exhibited horizontal point spacing that prevents large scale reconstruction of filament topography or fine scale flatness deviations.

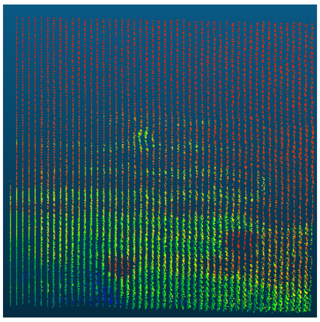

Figure 10: Representation (CloudCompare) of the component surface captured using LiDAR scans (TUD, Chair of Optical 3D-Metrology, 2025)

The method is therefore, in its current form, not suitable for evaluating the surface quality of additively manufactured concrete components.

4.7 Structure from Motion (SfM)

The SfM method using a standard 16 MP digital camera has demonstrated the highest robustness and the greatest information content in tests. Based on image data, a dense 3D point cloud can be generated that maps the surface geometry over a large area and in great detail. The method reliably maps both the filament structure and large-scale flatness deviations. If tolerances, e. g. according to German standard DIN 18202, are to be complied with as part of a contract, the corresponding limit values can be stored behind the 3D model generated by SFM or the resulting point cloud in suitable 3D point cloud analysis software (Figure 11). [8]

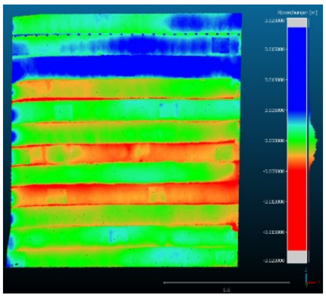

Figure 11: Representation (CloudCompare) of the SfM image of the component surface with stored reference plane (TUD, Chair of Optical 3D-Metrology, 2025)

The generated geometry is largely noise-free and allows conclusions to be drawn about wall curvature, filament flow, layer offset and joint shape. In addition, the acquisition of RGB data enables a supplementary analysis of colour uniformity and thus also of surface roughness and gloss. Macroscopically visible cracks and pores can also be evaluated using automated image analysis. Accordingly, SfM is the most comprehensive method for large-area quantitative and qualitative surface analysis among the methods tested. On this basis, automated evaluation of the component surface is possible, so that the final quality assessment can immediately determine whether the component meets the required contractual specifications or not.

4.8 Evaluation of the investigated methods

The surface capture methods examined differ significantly in terms of their accuracy, information content, practical applicability under construction site conditions, and the capture dimensions covered. Table 1 provides an overview of which of the (semi-)automated methods for capturing acceptance-relevant criteria (see (9) in Figure 4) are suitable for use in the control loop in order to expand the as-built model with relevant geometric and optical information about the components. On this basis, an automated, objective evaluation of the component surface can be carried out, enabling an immediate and comprehensible decision as to whether or not the component meets the contractually specified requirements. In this context, the SfM method and manual laser line projection show great potential due to the combination of RGB data and depth information, providing both surface and geometric data.

Table 1 Overview of surface capture systems

System	Layer-Geometry	Flatness	Texture	Pore/ Crack	Colour/ Gloss
MLP	(✓)	✓	(✓)	✓	✓
TM	(✓)	✓	X	X	X
LS	✓	✓	✓	X	X
Li	X	✓	X	X	X
SfM	✓	✓	✓	✓	✓

5 Results and Conclusion

The present results illustrate that the quality of additively manufactured concrete components is primarily determined by the robotically controlled process guidance. Filament and layer related deviations have a direct impact on the global component geometry and surface characteristics, making robotics itself the central quality actor. The integration of process proximate sensor technology, in particular laser triangulation and structured imaging, into real time control loops enables for the first time adaptive compensation of material and environmental variabilities during printing. This allows a “first time right” production that systematically detects and corrects errors before they manifest in global component characteristics.

Automated acquisition of filament and layer related characteristics forms the basis for digital as built models that represent not only geometric but also morphological and optical surface parameters. Expansion of this data foundation, in particular with final acceptance data from SfM and evaluation of RGB data from the manual laser line, allows a complete and objective assessment of defined surface qualities. At the same time, linking process, sensor, and component data opens new possibilities for predictive quality algorithms that can further optimize robotics and automation based on machine learning approaches.

In the future, robotics control, process automation, and sensor based quality control should be coupled even more closely to operate additive manufacturing systems robustly, reproducibly, and in compliance with standards under variable construction site conditions. This represents a paradigmatic advancement: quality is no longer assessed retrospectively but becomes an integral part of the robotic manufacturing process, making additive manufacturing of concrete components industrially scalable and process reliable.

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