



Material characterization of workability and process imaging for robotic concrete finishing

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Abstract

In this paper, we discuss a robotic-assisted concrete finishing method for fabricating architectural panels. Concrete finishing is an important process for producing architectural elements with acceptable surface quality. It is also a challenging process conventionally relying on skillful laborers. We describe a hybrid framework incorporating both human skill and robotics in the concrete finishing process and a multi-phase sensing strategy to assist in part touch-up and to validate final surface quality. The paper discusses a general approach to finishing from three perspectives: (1) Material characterization of concrete's workability throughout its setting process, (2) A modular system-architecture for collaborative human-robot concrete finishing, and (3) Assessment feedback of surface quality using process images.

Keywords Robotic Concrete Finishing · Quality Control and Inspection · Process Image

1 Introduction

This paper describes a general framework for and test implementation of a shared human/machine approach to concrete finishing for architectural construction. The project is an extension of previous work on Profile- 3D-Printing, a novel manufacturing process for robotically printing architectural facade panels with thermally tuned surface geometries (Bard et al. 2018a). Further description of previous work will be detailed in Sect. 2.3. This paper will focus on the more general challenges of concrete finishing of architectural elements when combining human labor and industrial automation technologies. In particular, the paper will discuss three interconnected topics: (1) Material characterization of concrete throughout its setting process, (2) A modular system-architecture for collaborative human and robot concrete finishing, and (3) Assessment feedback of surface quality using process images.

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2 Background

2.1 Robotic fabrication for concrete applications

Automation technologies have been widely adopted in large-scale, manufacturing industries. Construction-related industries, historically late adopters of these technologies, have not yet realized the full potential for safer and more efficient building approaches or for extending the limits of architectural design, enabling more creative and customizable architecture (Giftthaler et al. 2017).

This paper focuses on automation in concrete construction, one of the most widely used building materials around the globe. Site-cast concrete still heavily relies on skillful laborers to place and finish architectural elements (Wangler et al. 2016). With the convergence of digital technologies and computer-aided manufacturing, novel methods promise alternative strategies for concrete construction. Additive manufacturing (AM) is one approach with the potential to highly impact the concrete Industry. AM describes a group of processes that typically produce objects by layer-wise deposition and can achieve global shape without the use of molds (Paolini et al. 2019). The majority of concrete 3D printing research to date has focused on the mechanisms for precise delivery of concrete in 3D space and fine-tuning the rheological properties of concrete mixes to allow for ease of delivery, and to avoid material slump and cold joints after

deposition (Lim et al. 2012). In contrast to layer-wise extrusion, the Shotcrete 3D Printing (SC3DP) technique sprays concrete with pressure to create a 3D structure (Neudecker et al. 2016). Subtractive methods, in which layers of materials are removed to produce a desired geometry, have also been applied in concrete manufacturing (Bruckermann and Alberdi 2010). A smooth doubly-curved concrete element has been fabricated by combining the SC3DP and subtractive post-processing (Hack and Kloft 2020).

While these approaches hold tremendous promise for the construction industry, they tend to focus on the global shaping of concrete for architectural forms, essentially replacing cast-in-place formwork. Robotic concrete finishing for architectural components with complex surface geometry still remains an open research question. The prevalence of flatwork during building construction points to the fact that concrete finishing is central to on-site construction practices, and reminds us that it is a labor-intensive, multi-step process. Our approach to addressing the problem of concrete finishing in AM is inspired by metamorphic manufacturing (Spanos et al. 2019), a term describing methods that combine incremental deformation of materials with the precision and control of intelligent machines and robotic systems. Our research focuses on incremental morphing by strategically redistributing concrete material during its curing. This requires careful characterization of the material as it sets, and feedback regarding finish quality during the shaping process. Concrete deposition (concrete 3D-printing) and concrete finishing are not mutually exclusive. In fact, we anticipate that they can be combined to great effect for on-site construction.

2.2 Surface assessment and finish quality

Because concrete finishing requires multiple stages with specialized tools at each step, continual assessment of concrete surface quality is required throughout the fabrication process. Manual inspection of surface defects can be labor-intensive and error-prone. A large body of research focused on overcoming the limitations of manual inspection of concrete. However, this research mostly focuses on detecting defects in concrete for post-evaluation safety and maintenance purposes. For example, Abdel-Qader et al. compared four edge detection techniques (Canny edge detector, Sobel edge detector, Fourier transform and fast Harr transform) to detect cracks in concrete bridges (Abdel-Qader et al. 2003). Hutchinson and Chen introduced a procedure for selecting an appropriate threshold in edge detection (Hutchinson and Chen 2006). Sinha and Fieguth showed that Canny edge detection and Ostu's thresholding performed better in the test of crack detection based on underground pipe images, compared to conventional techniques (Sinha and Fieguth 2006). Suwwankarn et al. proposed air pockets detection

approaches using 11×11 pixels and 5×5 pixels circular pockets (Suwwanakarn et al. 2007).

In this project, our focus is on material characterization and surface assessment of concrete during its workable, pre-hardened phase for improved overall finish quality. With the introduction of sensing and real-time robotic manipulation, we aim at optimizing robotic finishing to produce fine quality concrete components for architectural applications. To quantitatively evaluate surface finishing, we proposed a framework involving multiple scanning and computer vision approaches throughout the multi-step robotic finishing process described in detail in Sect. 3.

2.3 Previous research

This research is built upon previous work by a team of researchers at Carnegie Mellon University exploring additive manufacturing and concrete construction. This team developed profile-3D-printing, a hybrid additive and subtractive process combining deposition of concrete for a rough layup with precision tooling for surface finishing (Bard et al. 2018b). The motivation for inventing this technique was rooted in the design of geometrically actuated, high-performance building components that are thermally tuned to passively reduce heating and cooling loads (Cupkova and Promopattum 2017). Hybrid additive manufacturing enables automated tooling of soft and phase-changing materials to achieve fine feature resolution and finish quality independent of print nozzle size, enabling high customization without significant increases in production time (Bard et al. 2018c). To evaluate the quality of concrete surface finishing, multiple scanning techniques have been reviewed for various robotic applications (Bard et al. 2016). Among them, we developed a method based on convolutional neural network to detect and classify discrepancies between virtual and target models and as-built realities. The method is both flexible enough to ignore construction tolerances while detecting specified flaws in various parts (Bard et al. 2018d). Expanding on this prior work, in this study, we developed phase-based scanning and evaluation techniques for robotic concrete finishing. With the integration of material properties at each stage of concrete finishing, the adaptive scanning technique provides critical support for evaluating surface quality, and repairing surface defects before the final set.

3 Methods

3.1 Process overview

In this section we will describe the development of a phase-based approach to concrete finishing and quality evaluation. To begin with, we will explain in Sect. 3.1.1 our approach

to characterize three phases of workability for concrete by measuring penetration resistance over time. Based on the distinct material properties of each workability phase described in Sect. 3.1.2, we will explain in Sect. 3.1.3 how we built a hybrid scanning system consisting of both two-dimensional imaging and three-dimensional scanning and defined adaptive thresholds for each phase. Finally in Sects. 3.3–3.5 we will describe each step of the finishing and touch-up strategy combining human tacit knowledge and robot precision.

3.1.1 Material characterization

Concrete workability, quantified by concrete slump is an important property of a concrete mixture, which is known to affect the consistency, flowability, pumpability, compactability, and harshness of a concrete mix (Mehta 1986). Intensive test methods have been proposed to evaluate concrete workability in the large body of literature existing on concrete rheology (Ferraris et al. 2001). Most of the definitions of workability are descriptive and subjective (Ferraris 1999). For example, according to the American Concrete Institute (ACI), workability is a property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, compacted, and finished. Several studies have been done to define the workability of concrete in quantitative terms which can be physically measured. For example, Ritchie proposed three properties: stability, compactability and mobility to define the flow of concrete. (Ritchie 1962) Tattersall et al. provides both empirical and fundamental quantitative methods for defining concrete workability (Tattersall 1976). Fundamental quantitative metrics such as viscosity and yield stress can be used in conformity with qualitative descriptions and physical

measurements. In this study, we characterized three stages of concrete workability by concrete penetration resistance. After mixing, concrete experiences a fresh stage, initial set stage, and final set stage until curing. For each stage categorized by preliminary material testing, we developed customized fabrication and evaluation strategies. (As can be seen in Fig. 1).

We used the penetrometer test as a standard onsite testing method to measure the set time. We first sampled a portion of mortar to fill a rigid cylindrical container to a depth from 152.4 to 177.8 mm. After one to one and a half hours after mixing, we conducted an initial penetration test using a concrete pocket penetrometer with a rod of a hemispherical end. The tip area of the rod is 32.3 mm². To collect the penetration resistance data, we made 6 to 8 penetrations at a 20 min interval. We plotted the mean value and standard deviation of penetration resistance at each time of setting in Fig 1. We used the test result as the benchmark to describe concrete status. According to The American Concrete Institute (ACI), 500 psi is the initial set of the concrete, before that point, concrete is workable in global shape. Based on that information and actual experiments, we identified the optimal time frame for different working procedures.

At the fresh stage, the penetration resistance of the concrete is below 120 psi. The concrete is still liquid, plastic, visco-elastic and workable, which is ideal for the rough pass. The rough pass removes excessive materials and shapes the concrete panel surface according to the 3D model. After the fresh stage, a stiff skeleton starts to form and the concrete gradually becomes rigid, characterized by penetration pressure ranging from 120 psi to 350 psi. At the initial set stage, the initial finish process was conducted to refine the surface quality until it passes the automated surface quality assessment based on computer vision. The third stage, the final set

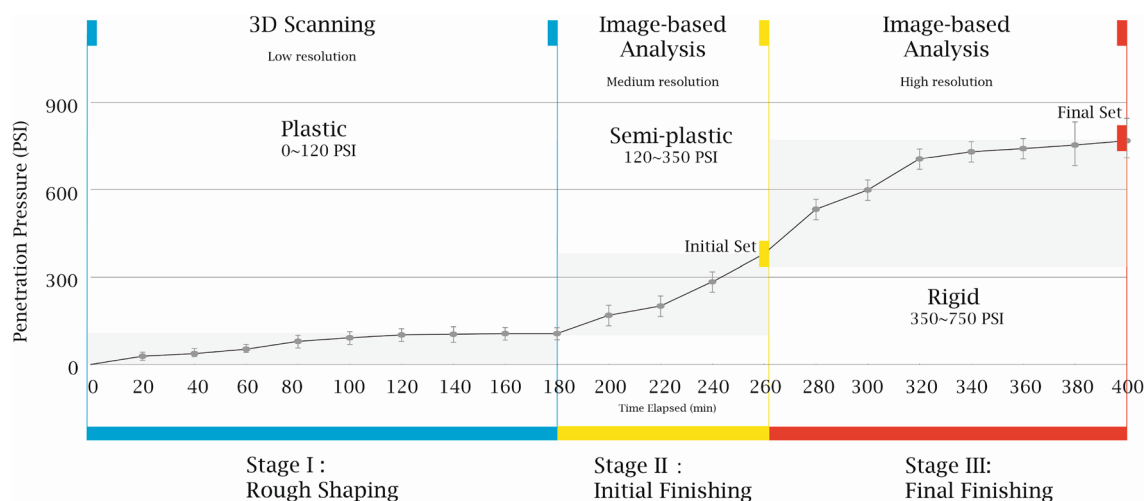


Fig. 1 Three phases of early age concrete characterized by penetration resistance

stage, begins after the point of the final setting. At this stage, the strength of the concrete increases rapidly from 350 psi to 750 psi. Meanwhile, air pockets emerge as water on the concrete surface evaporates due to the hydration heat. The final finish process fills the air pockets and smooths for final surface quality.

3.1.2 Three-stage approach

In the previous paper published by the research team, the Profile 3D printing concept was introduced and illustrated by fabricating concrete components with complex 2.5D geometries. The project group continues to strive towards creating an industry-ready technology for concrete surfacing finish to produce a high-quality architecture product. Figure 2 gives an introduction to the current state of the project, manufacturing procedure, its main actors and stakeholders, as well as the main current areas of research. From Sects. 3.2

to 3.5, we will elaborate a three-stage approach including roughing, shaping, and finishing. In each section, we will discuss stage-specific properties and strategies for scanning and toolpath planning.

3.1.3 Touch-up and quality control

The touch-up routine is conducted in two modes, fully automated mode and shared autonomy mode. At the end of each phase, the system will scan the concrete panel surface. If the number of detected defects exceeds a predefined threshold, the system will generate suggestive tool paths for repairing the defects and compile a routing based on the tool paths. In fully automated mode, the defect repairing routine is conducted recursively until no defects can be further detected. However, in most cases, manual intervention is required. Thus, in shared autonomy mode, the system highlights the defects which are constantly detected after the automated repair routine. Then, the operator will evaluate the current

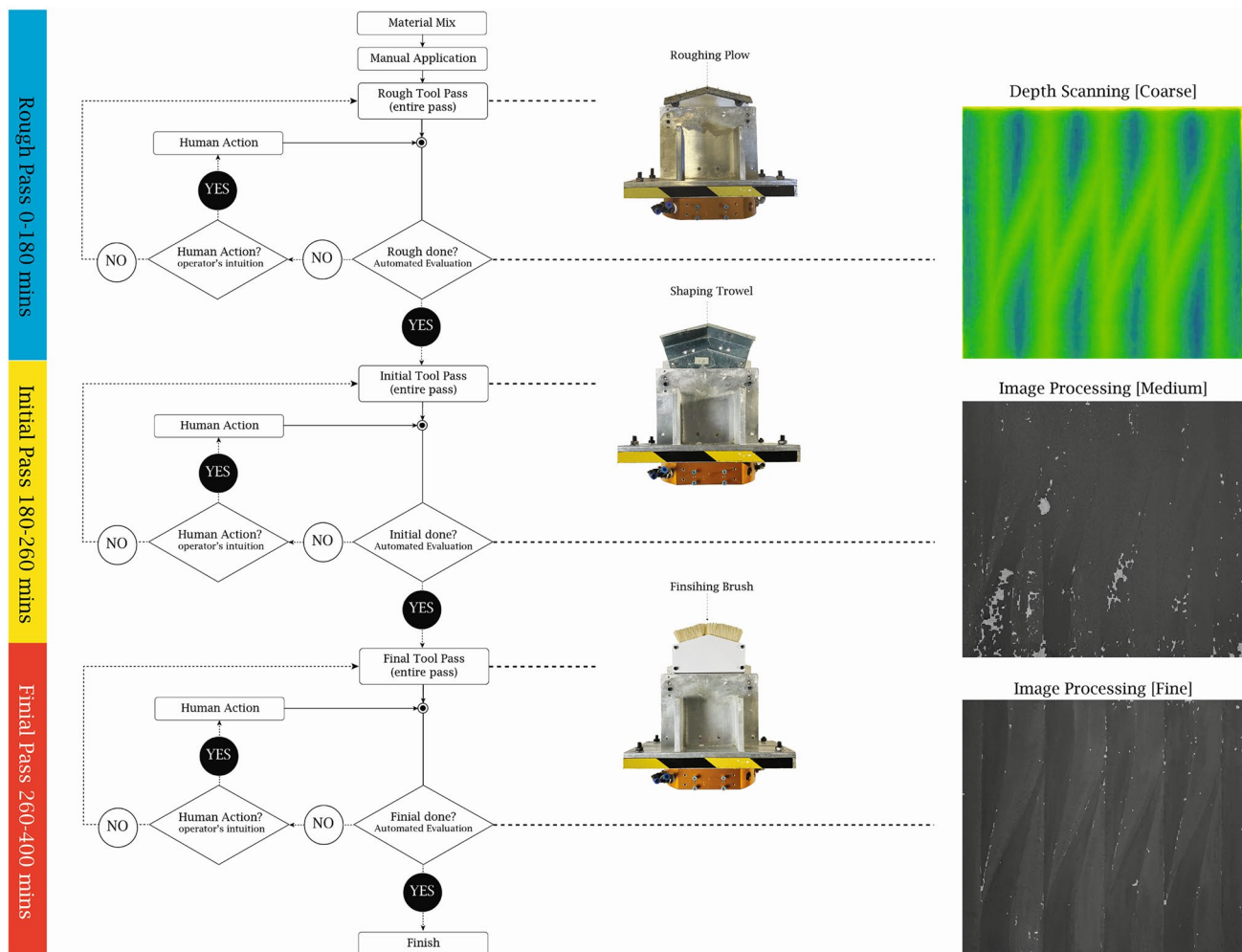


Fig. 2 Flow chart of the manufacturing process and the corresponding tools and scanning methods

state and make a decision to either manually repair the defects or authorize the start of next phase.

3.2 System overview

3.2.1 Workcell, hardware, software

The work cell we used for this project consists of an *ABB IRB 6640* robotic arm, a set of customized end-of-arm tooling including an aluminum tool chassis to receive manually interchangeable profiling plates, and an assessment toolkit for each phase such as Kinect, camera and structured light scanner.

The software system consists of three modules: 3D modeling, robotic manipulation and sensing.

– 3D modeling module

The modeling module stores geometrical data of concrete panels. Built upon Rhinoceros 3D and Grasshopper, the modeling component provides a user interface for users to monitor the fabrication process and modify the panel surface geometry. The model of the concrete panel is constructed parametrically. Users can experiment with multiple design options by tuning the parameters that define the global and local geometry of concrete panels. Based on the surface geometry of concrete panels, toolpath can be created and streamed to the robotic manipulation component, which translates spatial data into machine code for ABB robots.

– Robotic manipulation module

The robotic manipulation module is implemented in Microsoft C++ based on Open-ABB with a communication protocol in Python.

– Sensing module

The sensing module processes information gathered from Kinect and camera, then reconstructs and assesses the status of concrete panels in real-time. The sensing component is implemented using Microsoft Visual C++ and Open CV (Intel Open Source Computer Vision Library). The design and fabrication of concrete components involve multiple varied platforms and different file formats.

3.2.2 Shared data structure

To assist in the accumulation of all relevant data along the life cycle from design to fabrication, we developed an integrated data schema based on uniform format, pixels. As shown in Fig. 3, by aligning multiple layers of data in pixel

format, we built a relational data system, thus information from each layer can be cross-referenced. This approach builds upon the use of intrinsic images in computer vision. Intrinsic images are, “A set of images used to represent characteristics of a scene pictured in an image, with each image representing one particular characteristic of the scene.” (Tappen 2014) We extend this approach by also including process images, whereby we represent the fabrication sequence as a series of color masks aligned to the overall pixel data schema. For instance, by coupling the toolpath data and depth data, the assessment of the concrete panel surface can directly guide the robotic manipulation. If the number of surface defects found in the depth map exceeds the threshold, it will trigger the execution of the toolpath, the area within reach of which can cover the imperfect area on the concrete surface. To implement the shared data structure, we used the GHPython Component in Grasshopper to automatically generate a binary image for each toolpath. Grasshopper is a visual programming tool provided by the Rhinoceros 3D computer-aided design application. For a binary image P_i of resolution $n \times n$ associated with toolpath i , the pixel value at the position j is determined by whether it is inside (partially inside) or outside the boundary of the region covered by the toolpath i . If the pixel is inside the boundary, the pixel value is set to 1, otherwise to 0. We use an image-based approach to represent toolpaths in pixels (Fig. 4). The approach provides an efficient and uniform data format from design to manufacturing.

We use JSON (JavaScript Object Notation) schema for data management and exchange. Each panel is stored with a unique panel ID and metadata including the file path for toolpath masks, the machine code for each toolpath, the CAD file of the panel, and the bill of materials.

3.2.3 Graphical user interface

In order to inform the operator about the status of the ongoing task, we developed a graphical user interface (GUI) for reading and visualizing the data of sensors, materials and robots (Fig. 5). The GUI for the concrete surface system is composed of four panels: the phase navigator panel, the time tracker panel, the task management panel and the data analytics and visualization panel. The phase navigator panel provides users with sequential information on the three stages and their transition zones in concrete finishing. The panel encodes major steps in concrete finishing for users to track the overall progress. The time tracker panel tracks elapsed time and provides a default template of the task duration. The template can be modified empirically, according to material characteristics and environmental factors, such as moisture and temperature. The action panel is for users to control the robot by either authorizing or overwriting the suggested next action. The data analytics and

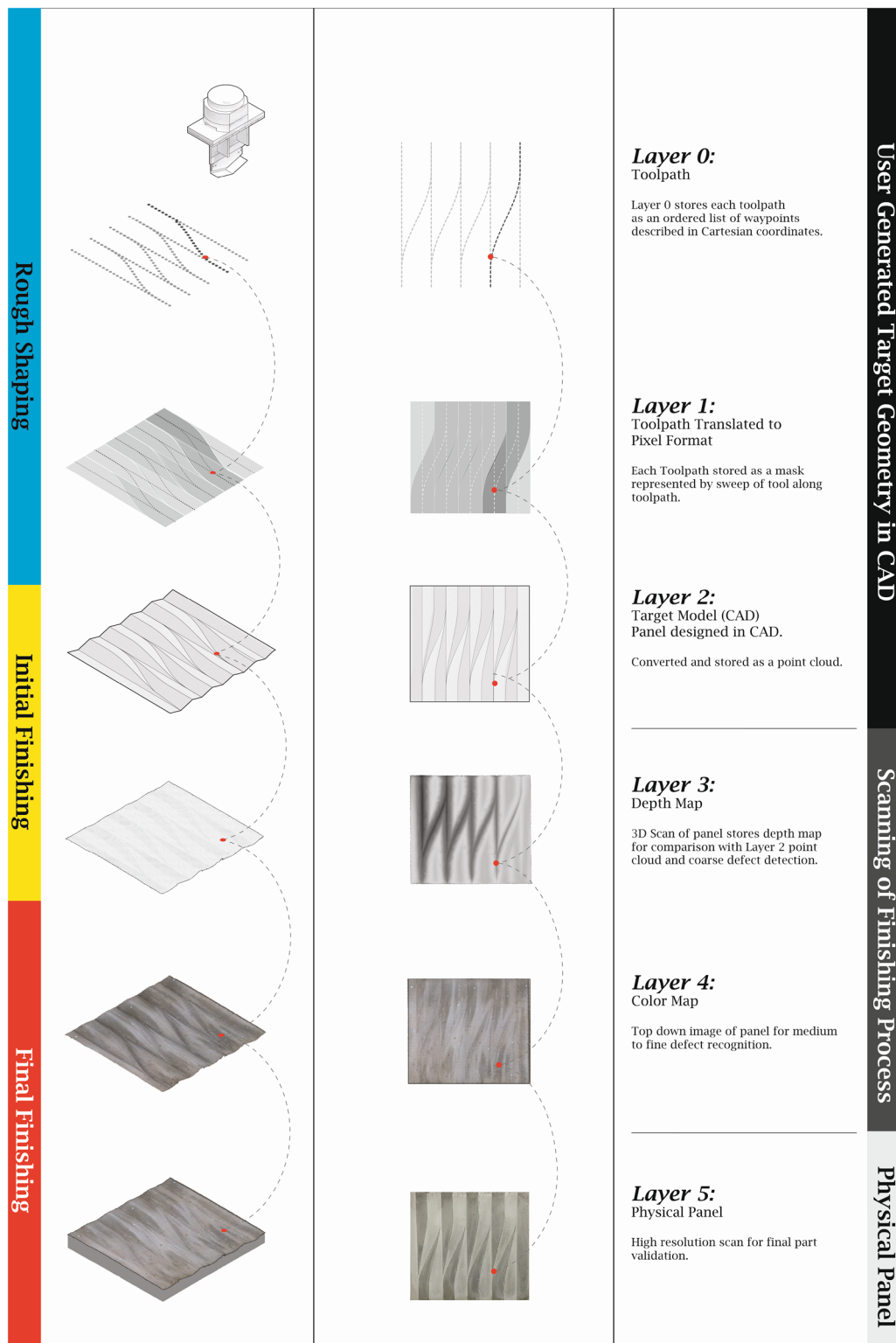


Fig. 3 Shared data structure and intrinsic imaging

visualization panel is the main display area for equipment status, sensor data surface quality evaluation result and CAD model of the concrete panel.

In order to obtain a platform and database independent application, we chose to implement the concrete surface finishing system in the Python programming language. The

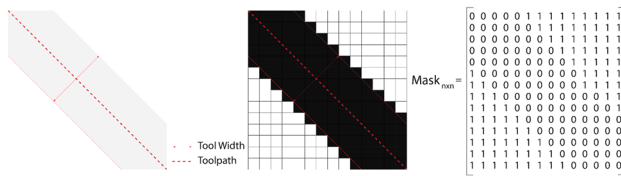


Fig. 4 Representation of a toolpath in pixel format

design data such as CAD file and toolpath was exported from Rhinoceros 3D and stored in a file system organized by panel IDs. The data was then read and stored as an instance of the panel class. When the robots and sensors are active, the data generated is streamed in real-time via UDP protocol. The GUI is implemented based on PyQt5, a cross-platform GUI design toolkit for Python.

3.3 Roughing

3.3.1 Stage specific material characterization

At the fresh stage, the penetration resistance of the concrete is below 120 psi. The liquidity of the concrete is ideal for the rough pass. After the fresh concrete is distributed on the work table, the robot executes the first rough pass (analog to screeding in traditional concrete work (Spahr and Johnston 2014)), shaping the fresh concrete into the approximate form of the desired end product. Human supervisors are

responsible to make small adjustments in the roughing task: filling in areas with insufficient concrete, cleaning the tool, stopping the process and reiterating the process if necessary.

3.3.2 Scanning approach

At the fresh stage, we use a Kinect sensor to catch depth images and evaluate the surface quality (Fig. 2). The Kinect sensor package consists of an RGB camera, which is used for capturing normal color images, as well as an infrared camera and emitter pair for depth sensing. The data acquired from the sensor including a color image array with dimensions 1920×1080 pixels and an Infrared image array with dimensions 512×424 pixels. We use a checkboard-based calibration scheme to calibrate color images and depth images jointly (Zhang and Zhang 2016). By correlating depth image and color images, we obtain a 3D coordinates array with dimensions of $512 \times 424 \times 3$. We compare the scanning result from the Kinect sensor with the CAD file to find locations where the absolute difference of z-value is larger than 5 mm. Due to the noise of the Kinect sensor, we use the depth-based scanning approach only for the roughing process to find regions with defects larger than $3 \times 3 \text{ mm}^2$. At this stage the working environment is messy and the wet concrete could have reflective surfaces. To address this issue, Kinect scanning results won't be influenced by lighting settings and distance. Additionally, during the rough path, the surface defects are noticeable, we trade the resolution with

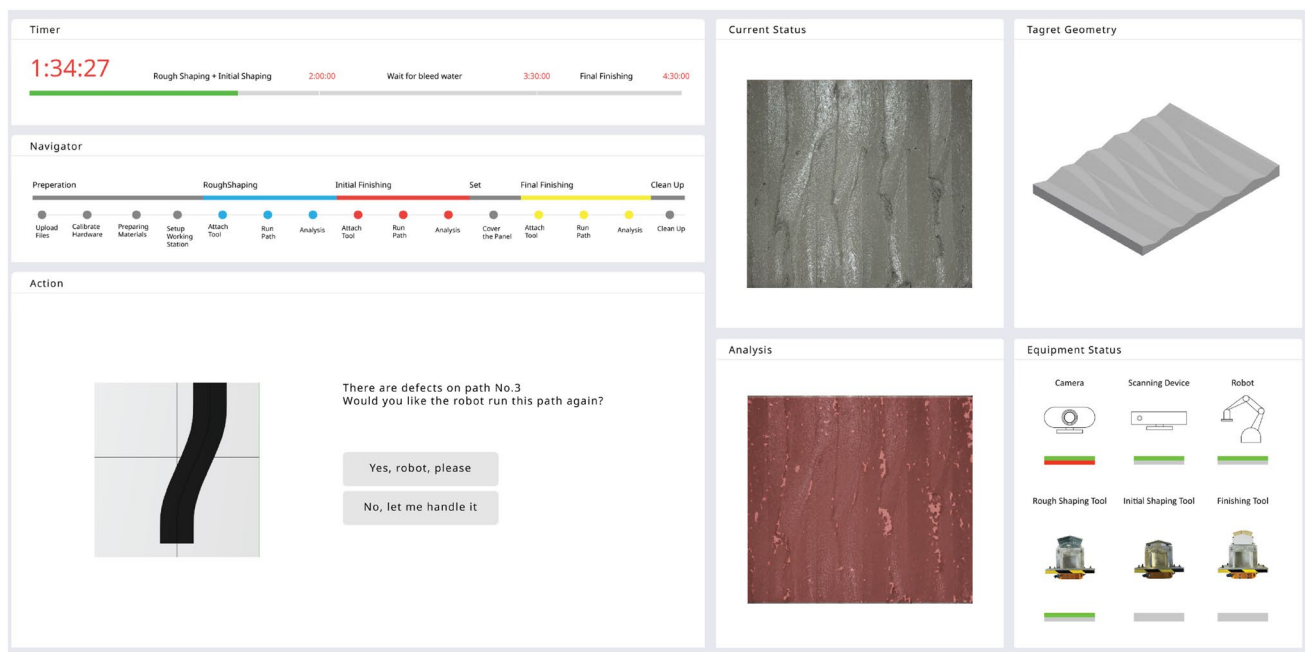


Fig. 5 Graphical user interface design for the concrete surface finishing system

a faster scanning method so that the system can reflect the surface quality in real-time. Therefore, Kinect with its low cost and high environment adaptability could be a reasonable option. For the roughing process, the threshold of surface irregularity size is set to ± 3 mm, this is the minimum size of objects the scanner looks at. The Kinect-based scanning approach ensures that surface defects over 3 mm can be detected and repaired at the fresh stage, small surface defects caused by air bubbles are addressed in the shaping and the final finishing process. We used a machine vision-based approach for detecting small surface defects which will be elaborated in Sect. 3.4.2.

3.3.3 Path planning and tooling approach

In the rough shaping process, the 3D printed trowel shape tool with a “V” shaped profile is used to remove excess material. As depicted in Fig. 2, in the back of the tool, we’ve designed a small plow-like attachment to remove excess material that usually gets pushed around at the

intersections to achieve more defined geometry. This tool was successful at removing material from the intersections, and efficiently shape out the rough outline for the next finishing process.

3.4 Shaping

3.4.1 Stage specific material characterization

After the rough tool passes, the initial finish, (analog to floating in traditional concrete work) can begin. At this stage, the concrete penetration resistance ranges from 120 psi to 350 psi. It is an ideal workability for shaping by compacting aggregates. The robot executes a tool pass in order to fully embed the larger aggregate under the surface and compact it so that it can be covered by bleed water during the concrete setting. Minor geometrical adjustments can still be made, however as the tool used for finishing is not designed for material displacement, the geometrical freedom is much limited, and all major adjustments should be already in place by the end of the previous step.

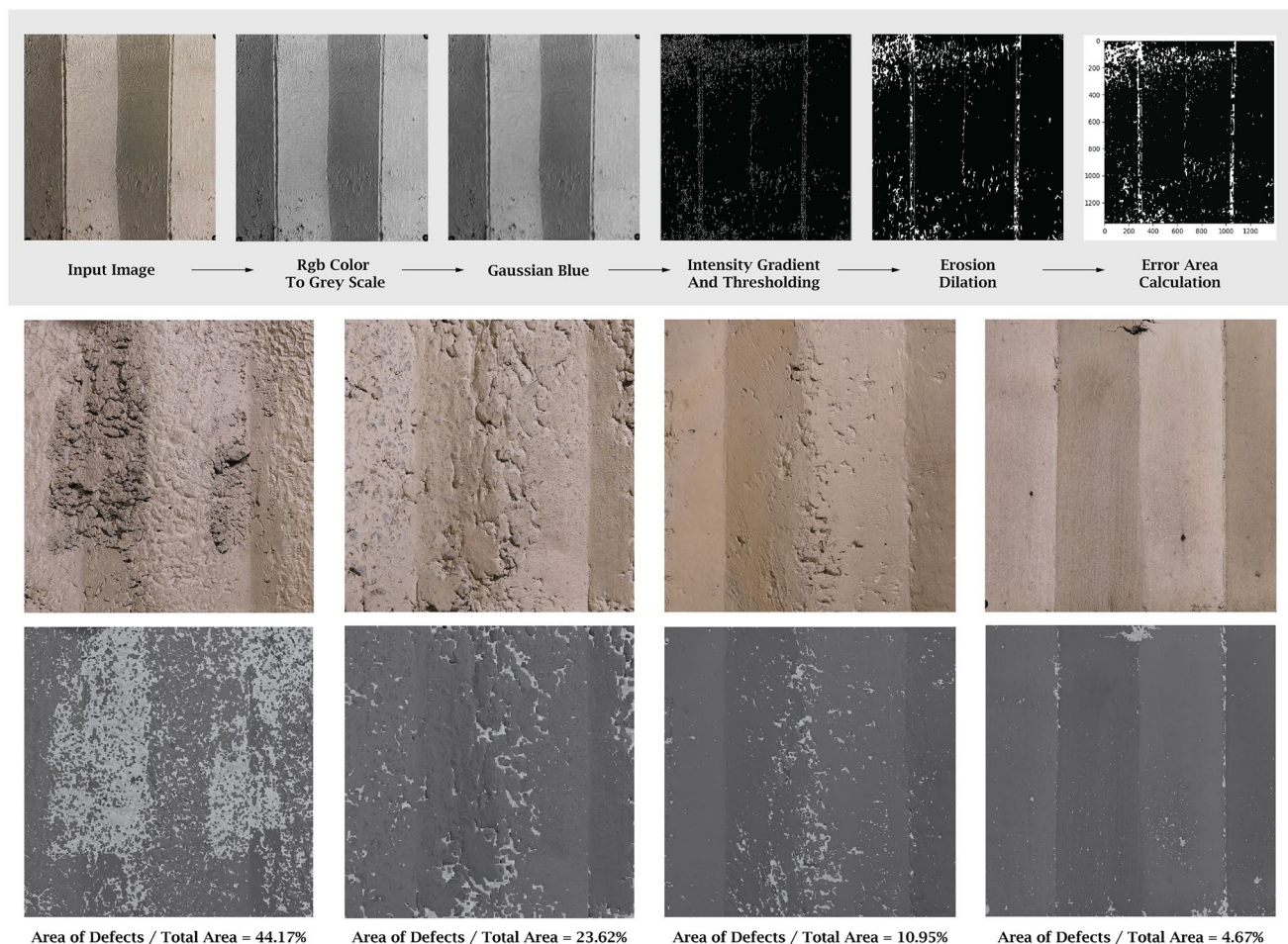


Fig. 6 Image-based surface quality assessment method and its application on panels with varied finishing quality

3.4.2 Scanning approach

We used a machine vision-based method to assess surface quality at this stage (Fig. 6). We used a webcam with a resolution 1920×1080 to take images from the perspective of the view perpendicular to the panel surface. At the shaping stage, bleed water on the panel surface can lead to specular reflections, which may affect defect detection. Thus, we first implemented a simple but effective method for specular highlight reduction. We computed the maximum diffuse chromaticity $\lambda_{\max}$ of the input image I . $\lambda_{\max}$ was used to guide the edge-aware joint bilateral filter. After iterative process, we removed specular reflections and extracted diffuse reflections of the input image. The detail of the algorithm was elaborated in multiple prior works (Tan and Ikeuchi 2005; Yang et al. 2010). The image with highlight removed was then converted into greyscale mode since for the initial finishing, we focus more on morphological defects such as air pockets instead of discoloration. Then we applied the 5×5 Gaussian filter to smooth the image and reduce the impact of noise caused by non-uniform illumination. To locate potential boundaries of defect, we built an edge detection pipeline based on the canny edge detector (Canny 1986). We calculated the intensity gradient of the image and used both high and low threshold to find pixels with distinct value. The morphological operators such as dilation and erosion were then applied to close the boundary of defects detected. After the area of defects is located, we calculated the metric to evaluate surface quality characterized by the defect rate σ which is defined by the ratio between the number of the pixels of defects and the total number of the pixels of the image. The proposed defect rate calculation is summarized in Algorithm 1.

3.4.3 Path planning and tooling approach

To reflect the floating process in traditional concrete work. We design a thin blade finishing tool, folded with a 32 gauge steel sheet in one piece. We also introduced vibration at the end of arm tool in an attempt to force the aggregate particles under the surface of the concrete, as well as establishing the optimal process parameters such as tool geometry, angle, speed etc. Lastly we tested oscillation in the Z direction in order to embed larger aggregate below the finishing surface.

3.5 Finishing

3.5.1 Stage specific material characterization

Following the initial finishing pass, the concrete is set for about 90 min. At this stage, the strength of the concrete increases rapidly from 350 psi to 750 psi. During the setting

process water and finer particles rise to the surface of the concrete, partially hiding the larger aggregate particles below. Once the initial set (traditionally defined as when max deflection due to foot pressure is less than ~ 6 mm (Spahr and Johnston 2014)) is achieved, the panel is ready for the finish tool pass.

3.5.2 Scanning approach

In the phase of final finishing, we run image-based surface checking with high resolution to evaluate the surface quality. Compared to the shaping stage, we changed the kernel of Gaussian filter from 5×5 to 3×3 and decrease the range of the edge detector for detecting smaller surface defects. Once the result matches our baseline, we can assume that the panel already meets the baseline, and the procedure can stop. To validate our surface quality control, we use a handheld 3D scanner with structured light (EinScan Pro) to obtain high-quality 3D models for gathering baseline information of concrete panels and archive the 3d model for future use.

3.5.3 Path planning and tooling approach

The final pass toolpaths are similar to the previous two passes. However, a soft tool, e.g. a brush or a sponge is used to stroke the surface of the concrete, closing the remaining small holes and bubbles. In many cases, multiple tool passes are not enough to eliminate all of air pockets. The operator needs to manually fix air pockets that cannot be repaired by robots. After the final pass(es), the edges of panels are trimmed off using a cookie-cutter-like cutting frame and it is moved from the worktable to a climate-controlled storage area, where the concrete cures over the next days, reaching its final strength.

4 Result

4.1 Overview of tests conducted

The team produced a series of test panels $15.2 \text{ cm} \times 25.4 \text{ cm}$ in order to optimize process parameters related to speed and path settings.

4.2 Finishing rate

We quantified the finishing rate by measuring the area a robot can cover in a minute. The metric can be roughly calculated by the multiplication of the tool centre point (TCP) speed of the robot and the width of the end-effector. For example, at the roughing stage, the TCP speed was set to 25 mm/s. The width of end-effector, the 3D printed trowel shape tool with a “V” shaped profile, is 10 cm. Thus, the

coverage area of a robot is 0.15 m^2 per minute. However, for most cases, it can take multiple iterations to achieve an optimal surface quality. For example, at the initial finishing stage, it takes 5–10 iterations to meet the requirement of surface quality evaluation. The number of iterations is sensitive to the complexity of the surface pattern and concrete workability. A detailed description of finishing rate of each stage is shown in the Table 1 above.

4.3 Improved finish level

We quantified the defect rate by measuring the ratio between the area of detected defects and the total surface area. The defect rate is a critical metric for quantitatively evaluating the success of a routine. As can be seen in Fig. 7, the defect rate decreases from 2.9 to 0.5% from rough shaping to final finishing. Compared with earlier results published in previous papers, our concrete surface finishing quality improved according to the defect rate. As can be seen in Fig. 8, the

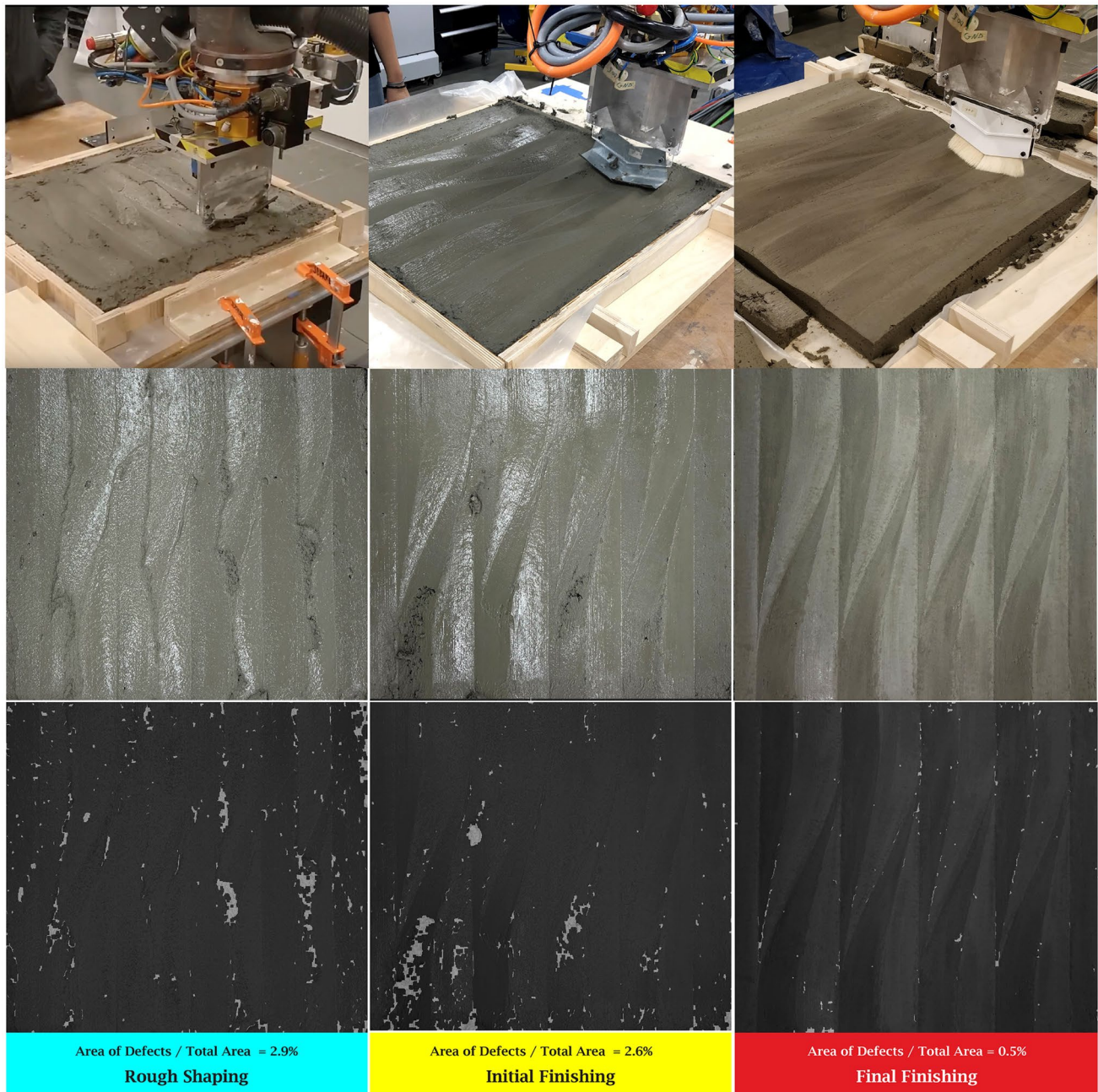


Fig. 7 Top view of final results and scanning based on computer vision

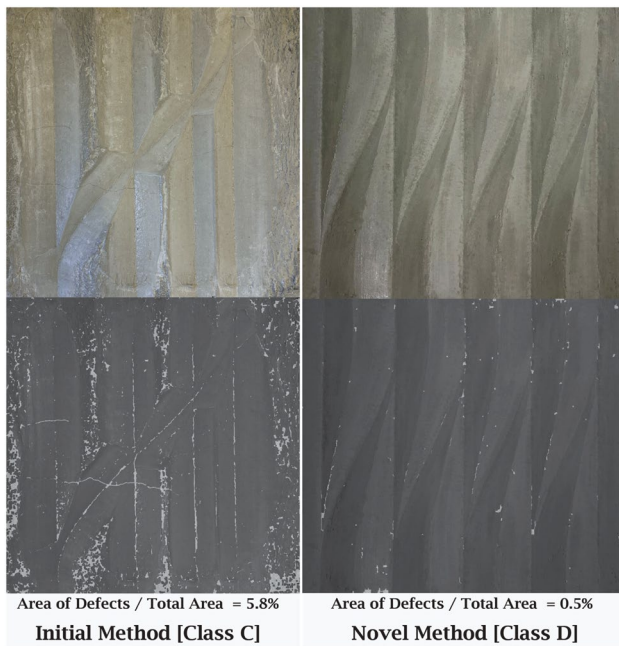


Fig. 8 Comparison between previous panel of class C quality and the panel fabricated with the novel method, which is categorized as class D quality

Table 1 Table showing the finishing rate at each stage

	Stage 1	Stage 2	Stage 3
TCP speed	25 mm/s	35 mm/s	45 mm/s
Tool width	10 cm	10 cm	10 cm
Finishing rate	0.15 m ² /min	0.21 m ² /min	0.27 m ² /min
Iteration	1~2	5~10	2~3

defect rate decreases from 5.8 to 0.5%. Additionally, based on the standard classification from American Concrete Institute, the finishing quality improved from Concrete Surface Category C to Category D after we adopted the novel method introduced in this paper.

5 Discussion

5.1 Current challenges and future work

One challenge facing concrete additive manufacturing approaches in general is the difficulty of incorporating coarse aggregate into the process. Lack of aggregate in concrete negatively impacts overall strength and material price by volume. Our team has begun testing the incorporation of 6.35 mm stone in our standard mix. The raw materials for fabricating a 152.40 mm × 304.80 mm panel with coarse aggregates include: 2.5 kg sand, 2.25 kg cement, 0.25 kg metakaolin, 7.5 kg stone, ~16 ml superplasticizer (SP), ~27 ml viscosity modifying agent (VMA). While we have not yet achieved ACI surface finish category 4 we are steadily improving overall finish quality with stone aggregate. To avoid surface defects caused by air bubbles between coarse aggregates, we add two vibration motor (3 V/1500 rpm) to the backside of the steel sheet in contact with the concrete panel surface. At the connection between the end effector and the flange, we mount a layer of rubber pad to partially cushion the vibration. We found that vibration can provide pressure for condensing coarse aggregates, which is helpful for eliminating surface defects. We also explored the impact of path planning on improved finish quality and found in initial tests that introducing a sawing motion along with Z travel of the tool improved results (Fig. 9). We plan to continue tests with stone aggregate in the future.



Fig. 9 Adding Z-oscillation into tool path can improve surface quality of concrete panels

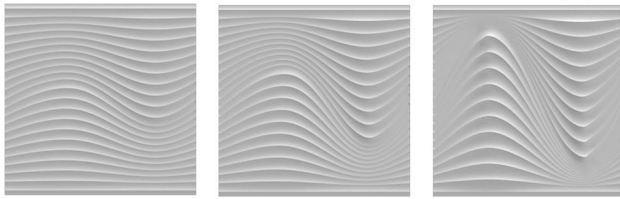


Fig. 10 Rendering of concrete panels with various design patterns

Currently, we demonstrated the robotic finishing process on a non-reinforced panel. The research team has worked on approaches to incorporate reinforcement such as layered short fiber and textile into the workflow. The depth of the concrete over the top fiber layer is above 50.8 mm. The depth of the finishing tool ranges from 25.4 mm to 31.8 mm. After finishing, the concrete cover to protect the fiber layer is above 19.0 mm. Another unmet challenge facing our team is the ability to coordinate the simultaneous manufacturing of multiple concrete panels using a single workcell. Because of the dynamics of set time and workability there are currently significant stretches of wait time in the finishing process. A single human operator and robot could work on multiple panels in a single batch and minimize downtime. Adding this functionality to our current user interface would allow for higher throughput. This will likely require an autonomous, non-contact strategy to verify penetration resistance for sequencing and timing across panels. It will also require an automated tool washing mechanism, which is currently a manual operation. Additionally, the proposed system works for surface finishing tasks with a horizontal set-up. The team has worked on surface finishing tasks for decorative plastering with a vertical set-up (Bard et al. 2018d). A vertical set-up for concrete surface finishing will be further explored. Finally, the proposed approach can be applicable to various design patterns by changing the shape of the cross section of tools and the shape of toolpaths. As depicted in Fig. 10, the team will explore and create taxonomies for design patterns and their associated tools and toolpaths. Previous studies on design variations can be seen in works such as (Bard et al. 2018a).

5.2 Summary

This paper described our efforts to improve and validate a robotic system for concrete finishing with human assistance. We have shown that with proper finishing techniques timed to concrete's material transformation during the setting process and robot supervision of defects, high quality (ACI CSC 4) surface finish can be achieved. Through this case study we also suggest that robotic finishing of hardset materials (e.g. ceramics, bio-composites) can be achieved through three main considerations: (1) material characterization of

workability during material set; (2) phased tooling and path planning in sync with changes in workability; (3) robotic oversight for defect detection and touch up. Improved concrete finishing in additive manufacturing could broaden the range of applications in the building industry especially where the striations left by layerwise deposition do not meet the required level of finish.

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Compliance with ethical standards

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