See - Sense - Respond:

An adaptive robotic fabrication framework for post-processing of glass fiber-reinforced plastic architectural panels

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The integration of robotic arms into architectural design and research has opened new possibilities for conceptualizing and materializing architecture. However, despite the precision and control, they have significant limitations related to sensing and responding to the physical environment. These limitations implicitly define what can be designed and built, especially in high precision and large-scale architectural applications. One such example is the robotic tooling of large-scale glass-fiber-reinforced plastic panels. In this paper, we present the first stages of research in which we employ computer-vision algorithms to augment the robotic fabrication process. This paper focuses on the technical implementation of this visually augmented robotic fabrication framework. The practical applications are kept secondary and are showcased with a simple experiment on robotic drawing.

Keywords: *Augmented Robotics, Adaptive Fabrication, Computer Vision, Human-Computer Interaction.*

INTRODUCTION

Glass-Fiber-Reinforced Plastics (GFRP) emerged as a durable, lightweight, and relatively cost-effective alternative in architectural construction and are being used to manufacture complex architectural geometries (Truong, 2020). The manufacturing of GFRP components in an architectural scale conventionally relies on high-level crafting skills and is labor-intensive. The integration of industrial robots into the manufacturing of GFRP components can provide more precision and control, reduce material waste, and significantly decrease the time required to manufacture the components. However, contemporary robotic fabrication workflows remain limited or often impractical in manufacturing GFRP components, mainly due to their limitations in seeing and sensing the fabrication environment and responding to its changes in real-time.

This paper presents the initial stages of research that we are working on in partnership with Kreysler and Associates, a leading architectural GFRP manufacturer based in California. To respond to our industry partner's growing needs to automate the GFRP manufacturing process, we proposed a study with three consecutive stages: (1) adaptive workflows that digitally capture the fabrication environment, (2) assistive workflows that perform informed tooling in accordance with the digital template and obtained digital capture data, and (3) continuous workflows that oversee the fabrication process in real-time. These modalities incrementally build on top of the previous stages and incorporate various computational methods to address the shortcomings of conventional digital fabrication workflows in large-scale GFRP panel manufacturing.

In the adaptive fabrication stage, which constitutes the primary focus of this paper, the goal is to generate accurate and precise digital representations of the molded GFRP panels using computer-vision (CV) algorithms. This geometric capturing pipeline will allow the digital twin to account for numerous environmental and material factors in manufacturing, such as shrinkage or warpage. In addition, this data will inform subsequent high-precision GFRP tooling operations such as milling and sanding and enable us to inspect the accuracy of the 3D representations with respect to the digital master of the fabricated GFRP architectural panels.

In this paper, we present the first stages of this research in which we explore the potentials and drawbacks of various computational approaches to geometric reconstruction and registration of the work environment using fiducial markers. Due to practical and logistical reasons, these early tests were carried out with small-scale fabrication tasks using simple conformal toolpath generation algorithms as a proof of concept.

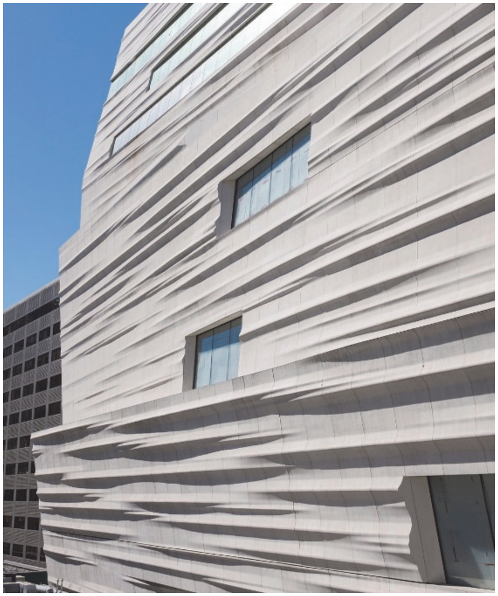


Figure 1
An example application of GFRP façade panels on SFMoMA Expansion Building. (Smith, 2016)

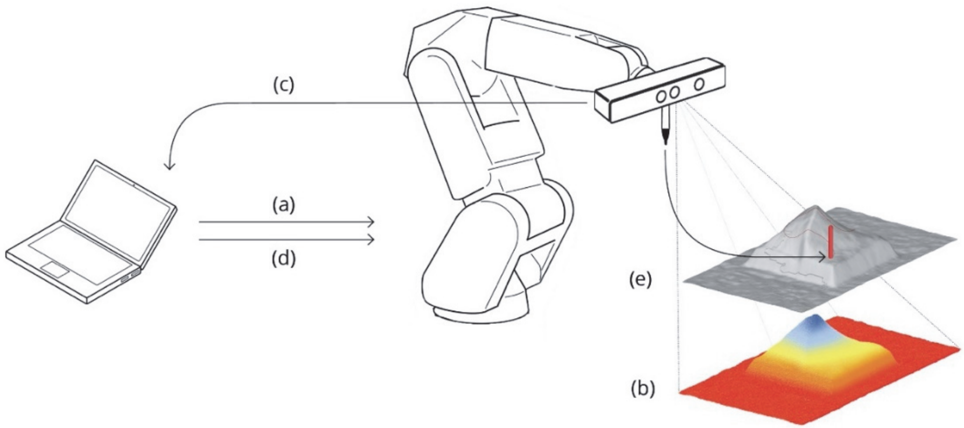
Our primary goal is to develop and document a relatively more accessible framework for accurately capturing the robot cell and establish an open-source foundation for future research dealing with complex design-fabrication scenarios to build upon. We strongly believe that the knowledge gained through this research has the potential to be generalized to wider architectural robotic fabrication settings and can be a crucial component in addressing complex tool-material interactions.

BACKGROUND

In both Human-Computer Interaction and Computational Design fields, where this research finds precedence, a growing number of researchers have been looking into the potentials of integrating various sensor feedback loops to address complex design-fabrication problems and material indeterminacy. Within this body of work, researchers explore the affordances of different sensing and actuating tools (Bard *et al.*, 2014; Moorman, Liu and Sabin, 2016). Other research efforts focus on vision-based systems to inform the digital representation and adapt tooling in accordance with the deviation between the physical realm and the digital representation (Dörfler, Rist and Rust, 2013; Schwartz *et al.*, 2014; Brugnaro *et al.*, 2016; Ercan Jenny *et al.*, 2020; Nicholas *et al.*, 2020). More recently, researchers began looking into how this established feedback loop can be utilized as a conversational method for designing within more interactive design-fabrication workflows (Zoran and Paradiso, 2013; Weichel *et al.*, 2015; Capunaman, 2020; Lee and Llach, 2020)

Within this body of work, we propose a computational framework for high fidelity reconstruction of the work object to inform subsequent fabrication operations and register the digital twin within the robot's coordinate system within tooling tolerances. Even though similar vision-based approaches to capture work environment exists in high precision fabrication scenarios such as the aerospace industry, these solutions are often black-boxed, task-specific and

Figure 2
Stages of the proposed adaptive workflow:
(a) scanning procedure,
(b) geometric capturing,
(c) registration, processing and reconstruction,
(d) conformal toolpath generation,
(e) tooling procedure.



challenging to generalize. Our goal through this exploration is to develop an open-sourced framework that can be adopted by the broader research community without sacrificing precision and computational efficiency while maintaining great control over the process.

METHODS

Building upon preceding research efforts in augmented and digital fabrication, in this paper, we present our initial efforts to establish a robust feedback pipeline to capture the work environment's current state and subsequently process it to inform the robotic fabrication process. Our experimental setup consists of an ABB IRB 120 robot with a custom pen holder end-of-arm-tool, a Microsoft Kinect Azure Developer Kit depth camera mounted on the end-of-arm-tool (EoAT). In addition to this hardware, we have also developed a Python script and a Grasshopper for Rhinoceros 3D definition to obtain and process the data from the camera and generate toolpaths for the robotic arm, respectively.

The computational framework we propose employs various computer vision and computer graphics algorithms to extract point clouds from the obtained depth image, register the reconstructed point cloud within the robot's coordinate system, segment and extract the object of interest and reconstruct mesh surfaces for future operations. These include algorithms from open-source libraries such as OpenCV (Bradski, 2000; *OpenCV*, 2021) and Open3D (Zhou, Park and Koltun, 2018; *Open3D*, 2021), as well as algorithms supported by the manufacturer developer kits (*Azure Kinect Sensor SDK*, 2021).

Figure 2 depicts the sequence of steps for 3D reconstruction of the region of interest and generation of the conformal toolpath. The proposed workflow begins with (a) offline programming of the robot procedure for scanning and (b) capturing RGBD images in MKV format. Once the scanning procedure is complete, the work environment is (c) reconstructed and registered. Reconstructed geometry is then imported into the Rhinoceros 3D environment for (d) offline programming of the adaptive toolpaths for tooling. Lastly, (e) the tooling procedure is carried out using a custom pen-holder EoAT.

The first challenge addressed was accurately capturing and registering the work environment in the robot's coordinate system. To address this challenge, we have incorporated ArUco markers (Garrido-Jurado *et al.*, 2014) with known locations with respect to the robot's coordinate system as registration keys. These markers allow point

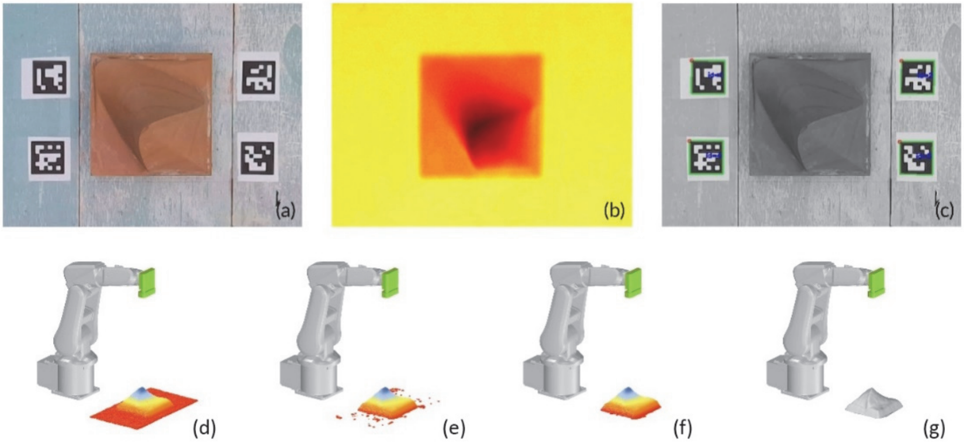


Figure 3
Stages of the 3D reconstruction pipeline:
(a) captured RGB image,
(b) captured depth image,
(c) detected ArUco markers,
(d) oriented and cropped point cloud,
(e) plane removal,
(f) outlier removal,
(g) surface reconstruction.

correspondences between camera robot coordinate systems and provide surface normal vectors for ensuring the reconstructed surfaces are not inverted. Additionally, since each ArUco marker is labeled individually, this approach allows the registration to be carried out even when some of the markers are not visible to the camera.

These fiducial markers were first extracted using the RGB camera to detect and label each marker using OpenCV. Knowing the pixel coordinates in 2D image space, these locations were then matched with the depth image to calculate the 3D position relative to the camera sensor. However, the time-of-flight (ToF) architecture used in Kinect Azure is prone to errors due to the infrared reflectivity of different materials, which often results in noisy depth measurements in the black regions of the fiducial markers. To circumvent that issue, we have developed an algorithm to find mean depth measurements for neighboring white pixels around the corner to validate the reliability of 3D depth information for these markers.

Using known point correspondences, we compute translation and rotation vectors between two coordinate systems and perform a rigid body transformation of the extracted point cloud from the camera coordinate system to the robot coordinate system. In extracting the point clouds from the captured RGBD image, we employed native Azure Kinect Sensor SDK functions in the Open3D library and the factory. Although we have carried out intrinsic calibration of the camera sensors using a

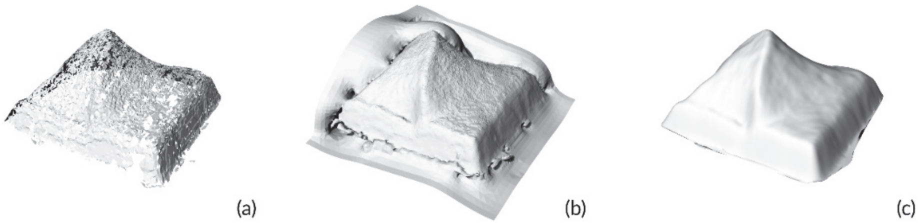


Figure 4
Results of
(a) Ball-pivoting,
(b) Poisson, and
(c) Delaunay Triangulation algorithms on surface reconstruction of the captured point cloud.

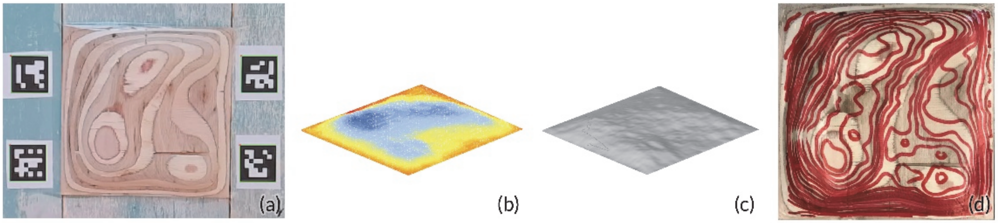


Figure 5
Testing of the 3D capture, 3D reconstruction, and 3-DoF adaptive toolpath generation pipelines:
(a) RGB image,
(b) color mapped point cloud,
(c) reconstructed mesh,
(d) tooling result.
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checkerboard pattern, our results were not significantly better than the factory calibration.

To reduce the computational complexity of future operations, the point cloud data is first cropped to the area defined by the four ArUco markers placed in the work environment. Then, the resulting point cloud is further processed by segmenting the ground using RANSAC plane segmentation and removing outliers based on the geometric clustering of the sampled points. Figure 3 shows sample images from different stages of the capturing pipeline and illustrates its stages.

Generation of the mesh surface from the processed point cloud has been tested using well-established methods in computer graphics as shown in Figure 4: (a) Ball-pivoting and (b) Poisson surface reconstruction algorithms natively implemented in Open3D, and (c) a custom Delaunay Triangulation definition in Grasshopper for Rhinoceros 3D. Although the native Open3D surface reconstruction algorithms were computationally more efficient, they repeatedly resulted in noisy mesh vertices and missing or intersecting faces, making it impossible to proceed to the next step of generating conformal toolpaths. However, the custom Delaunay Triangulation definition proved to be more robust for the sample surfaces tested within the scope of our early testing.

RESULTS

The proposed computational framework was tested for the accuracy of the geometric capturing, registration, and processing pipelines using a known surface for comparison. Throughout our testing, we opted for a simple conformal toolpath generation approach together with a spring-loaded custom pen holder EoAT (Figure 6). Throughout the tooling operation, we have closely observed the travel of the pen to have a rough estimate of the reconstruction error. We have observed that the reconstruction error is less than 3 mm during these tests.

We anticipate that this error might have occurred due to a combination of two major factors; (1) small variation in height in the CNC milled surface shown in Figure 5 and (2) inherent binning of depth measurements to the nearest millimeter value by the RGBD camera. These limitations can be best seen in the reconstruction results shown in Figures 4 and 5. Compared to the larger depth variation in Figure 4,

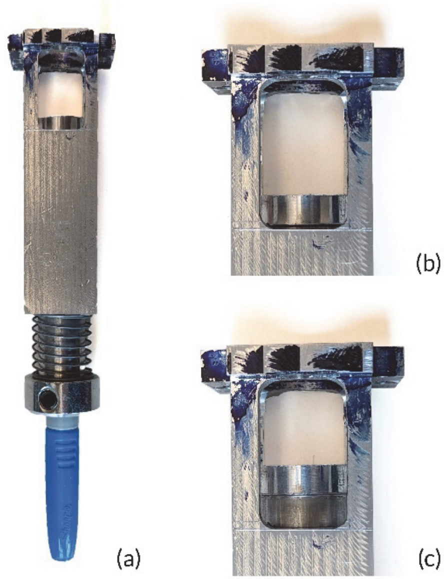

Figure 6
The custom pen holder EoAT:
(a) assembly,
(b) resting and
(c) compressed spring state.

geometry in Figure 5 suffers from such noise and reconstruction errors considerably more.

Although these early tests pinpoint some of the system's drawbacks and give a rough estimate for reconstruction error, such margins are well within the tooling tolerances used in various large-scale manufacturing applications. The proposed framework offers a novel interaction with industrial robotic arms, especially when another layer of sensor feedback is introduced into this workflow, such as constant force EoAT assemblies that can compensate for small deviations. Rather than relying on assumptions that the work environment is sterile and the work object is in ideal placement for tooling, this approach can incorporate messy and complex environmental interactions during fabrication.

DISCUSSION AND CONCLUSIONS

Although these initial tests are carried out at Penn State facilities through small-scale prototypes, we believe that the knowledge gained through this experiment is directly translatable to larger-scale applications. The problems of reconstruction and registration explored through this paper are universal and, for the most part, agnostic to changes in scale and tooling operations. We expect that most of the reconstruction and registration issues we have faced in our small-scale testing will be less prominent in large-scale applications as the work objects will inherently have a more significant variation in depth. We intend to test the validity of the proposed workflow in large-scale applications by carrying out various tests on our industry partner's facilities for robotic milling and sanding operations of GFRP panels.

Although our initial testing of the capturing pipeline yielded promising results, our future goal is to further refine the geometry registration by eliminating the need for physical markers using "Hand-Eye calibration" algorithms (Tsai and Lenz 1989) and utilizing the robotic arm's great range of motion capabilities for more accurate reconstruction. One major reason for exploring alternatives to fiducial markers in geometric registration is that the reliability of the registration results is directly correlated to the total number of markers visible to the camera at any given time. Since our intention is to explore large-scale applications, this would mean that the number of such markers needs to be increased drastically. Although such applications with a large number of markers are common in mass manufacturing settings, we believe that this might not be practical in architectural design-fabrication scenarios since each component differs considerably and complex geometries can easily occlude markers.

Another possible improvement is the real-time volumetric reconstruction methods for generating the digital twin (Curless and Levoy, 1996; Izadi *et al.*, 2011; Dong *et al.*, 2021), which can significantly improve the computational efficiency. Moreover, such an approach can help neutralize inherent issues such as perspective distortion, warm-up drift, and multipath interference (Tölgyessy *et al.*, 2021) by sampling a much larger set of camera poses for cross-validation.

The development of these frameworks will enable the tooling of GFRP panels without an a priori knowledge of the panel geometry and location and allow the robotic arm to adapt to inherent material indeterminacies observed during the GFRP manufacturing process, such as shrinkage and warpage. Consequently, we aim to reduce material waste through informed robotic tooling and streamline the incorporation of digital fabrication tools in GFRP manufacturing. As a distal contribution, we believe that the applications of the proposed framework can extend beyond automation concerns and address challenges in creative inquiries and complex tool-material interactions. Some of the areas that we believe the proposed framework can augment the fabrication process are on-site 3D printing of concrete, where the state of the work environment cannot be predetermined, and additive manufacturing using biomaterials such as mycelium, where the work object is continuously changing over time.

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