A Comprehensive Framework for Integrating Robotics and Digital Twins in Façade Perforation

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***Abstract*—In contemporary design practices, the conflict between initial design approaches and subsequent manufacturing and construction stages presents a notable challenge. To address this disparity, our study aims to establish a comprehensive digital design workflow, bridging these gaps. The authors introduce a conceptual framework that seamlessly integrates the imperatives of LEED with the realm of robotic manufacturing, specifically tailored for construction sites. The proposed methodology encompasses four distinct iFOBOT modules: iFOBOT-environment, iFOBOT-design, iFOBOT-construct, and iFOBOT-monitor. The integration of these modules allows for a holistic approach to design and construction, fostering efficient collaboration between multidisciplinary teams. To validate the efficacy of the author's approach, we conducted an empirical study involving the creation of a double-skin facade panel perforation using this integrated process. Initial findings emphasize the enhanced constructability achieved through simulated robotic interventions utilizing a heuristic function. Moreover, this research presents a functional prototype as a tangible embodiment of the method's practical application and potential impact on the field of architectural design and construction.**

***Index Terms*—Architectural design, Digital workflow, Integrated technology, Perforated facades, Robotic fabrication.**

I. Introduction

The contemporary construction industry has undergone a profound transformation, driven by the ascendancy of automated systems and robotics, resulting in a departure from traditional practices. This paradigm shift holds the potential to address entrenched profitability challenges while concurrently enhancing operational efficiency (Kontovourkis, Tryfonos, and Georgiou, 2020; Kurtser, et al., 2020). Within this dynamic context, the realm of on-site robotics has emerged as a focal point of both scholarly and industrial exploration, obtaining considerable attention. The applications of on-site robotics encompass a diverse spectrum, ranging from tasks such as milling, perforation, and inspection (Rea and Ottaviano, 2018) to the intricate oversight of structural safety monitoring. The rapid advancements of digital design methodologies have seamlessly integrated into modern manufacturing and construction frameworks, liberating architects from the constraints of conventional Fordist standardization. This transformative shift has ushered in a post-Fordist era, characterized by uncharted design possibilities (Abbasnejad, et al., 2021; Babatunde, et al., 2020; Yang, et al., 2020).

Embedded within architectural discourse, building information modeling (BIM) occupies a pivotal role, acting as a catalyst that unfolds architectural arrangements and many design possibilities, tailored to both pre- and post-rationalization design paradigms (Abbasnejad, et al., 2021; Babatunde, et al., 2020). This capacity to foster careful decision-making, resonating with an intrinsic harmony essential within the dynamic realms of dynamic and synthetic design, is seamlessly imparted to designers through simulations, thereby enhancing their computational ability (Ali, Lee, and Song, 2020b).

The seamless transmission of design attributes and limitations from upstream to downstream is hindered by the lack of anticipatory provisions within existing design methodologies and analytical resources (Babatunde, et al., 2020). The management of multiple robots under specialized semi-automated construction conditions remains constrained by the scarcity of robust and efficient programming techniques (Kontovourkis, Tryfonos, and Georgiou, 2020; Zied, 2007). Challenges inherent in such programming tasks include the constant evolution of the construction environment, significantly lower production volumes in building projects, and the diverse array of tasks involved (Hook, 2016).

This study advances the field by introducing and validating an integrated system, encompassing four integral modules: iFOBOT-environment, iFOBOT-design, iFOBOT-construct, and iFOBOT-monitor. These modules establish an end-to-end digital design workflow merging architectural creativity with robotic precision. The empirical exploration substantiates enhanced constructability and a transformative shift in how architectural design and construction synchronize. Amidst these imperatives, an integrated architectural robotics workflow is meticulously constructed, evading the limitations of proprietary software systems. The objective

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is a comprehensive framework unifying double-skin façade panel perforation following LEED (Leadership in Energy and Environmental Design), integrating architectural, climatic, construction, and quality assurance considerations.

II. Literature Review

A. Automation, Robotics, and Design Complexity in Architecture

(Kreig, 2022) stated that the computational design and robotic manufacture of segmented wood shells are well-suited to illustrate the performative possibilities at the intersection of complex geometry (Krieg, 2022). This research explored the use of robotics in building-scale projects. Three examples of this type of work were built using robotically milled planar shell segments, scanned and milled natural tree forks (Keating, et al. 2017), and robotically stapled timber slats (Willmann, et al., 2016).

This study offers a thorough summary of earlier investigations into automated building progress monitoring using 3D scanning and extended reality (XR) technologies. This compilation serves as a valuable reference, offering insights into the evolution of this field, the strengths and limitations of different methodologies, and the existing gaps that warrant further investigation for more robust and effective automated progress monitoring solutions as depicted in Table I.

B. 3D Scanning and Virtual Reality Integration for Automated Construction Progress Monitoring

In the context of automated building progress monitoring, this section critically assesses the integration of 3D scanning technologies with extended reality (XR) applications. The examination encompasses the implications and advancements resulting from the convergence of these technologies, offering a comprehensive analysis of their transformative role in reshaping the field.

Production monitoring (Ali, Lee, and ParkAli et al., 2020a), tracking hardware and inventory (Bosché, et al., 2014), and progress measurements (Rebolj, et al., 2017) all primarily rely on manual visual assessments and traditional progress reports. However, these practices are neither commonplace nor efficient, often demanding significant time investment and being susceptible to errors (Rahimian, et al., 2020). Expounding on this notion, Park, et al. (2013) outline a comprehensive three-stage framework for implementing augmented reality (Park, et al., 2013). The exploration of the utilization of BIM and AR/VR has accumulated extensive attention within various studies. Zied (2007) delves into mobile augmented reality software, wherein users capture screenshots from the web and previously collected images (Zied, 2007).

Despite all the developments, it is still difficult to create a practical workflow that allows designers to smoothly use simulation results as guiding parameters and restrictions throughout the early stages of design. A thorough and accurate construction monitoring system that covers the complete building, including both its interior and exterior domains, during the construction timetable is also lacking, according to prior studies.

III. Methodology

Expanding on previous research focused on the picking and placing of facade panels using a robot arm in the construction site optimization (Ali, Lee, and Song, 2021), the primary aim of this study is to introduce a methodology for constructing facades using a robotic arm integration with the design process, real-time monitoring, and environmental awareness, directly on the construction site. This expanded framework offers the idea of double-skin facade perforation as a cutting-edge construction method, building on the capabilities of the prior iFOBOT system, which included environmental analysis in the design phase and real-time monitoring during construction.

This study addresses several central research inquiries. First, it endeavors to develop a user-friendly facade design tool aligned with the environmental analysis criteria stipulated by LEED. Second, the study explores the combining of environmental analysis and robotic constraints into simulation-based performance assessments, thereby enhancing designers' decision-making processes. Finally, the research probes the feasibility of integrating iFOBOT technology to seamlessly synchronize the design phases of a

TABLE I

Technology, Solutions, Methodologies, and Gaps in Previous Research on 3D Scanning and Extended Reality Integration for Automated Construction Progress Monitoring

Study	Technology used	Solution	Methodology	Gap
Jenny, et al., (2023)	Mobile AR, Screenshots	Real-time progress tracking	Capture screenshots from the web and previous images to provide virtual information based on the user's role	Limited focus on mobile AR's potential for comprehensive progress monitoring
Kwon, Park and Lim (2014)	BIM, Augmented Reality	Enhanced inspection models	Integrating precise BIM data into AR markers for defect detection and quality control	Emphasis on inspection lacks exploration of broader automated progress monitoring
Hashemi (2021)	Augmented Reality	Fusion of physical environment with virtual elements	Three-tiered AR implementation: item identification, virtual object projection, and physical-virtual fusion	Primarily discusses AR framework, minimal focus on 3D scanning integration
Current Study	3D Scanning, Extended Reality	Comprehensive automated progress monitoring	Integrating 3D scanning for spatial accuracy and XR for real-time visualization	Investigates combining 3D scanning with XR for comprehensive automatic monitoring of construction site

wall in the construction site, relegating human involvement to the selection of design parameters and the supervision of the robotic arm's perforation activities. The proposed approach involves using an arm alongside analysis to carry out the perforation of a double-skin facade directly at the construction site. This system is called the iFOBOT, which stands for its components; "i" represents human involvement "F" signifies facade design and fabrication, and "OBOT" highlights the integration of the robotic arm, within the system's framework.

The proposed system architecture consists of four modules: (1) The iFOBOT-environment module is responsible, for conducting environmental analysis tasks to determine the foundational parameters of the double-skin façade, (2) the iFOBOT-design module generates a layer for the double-skin facade based on specifications obtained from the previous module, (3) the iFOBOT-construct module controls the movements of robot arms during the on-site perforation process and the iFOBOT-monitor module supervises the process, and (4) The iFOBOT-monitor module oversees the process. It is important to note that the graphical algorithm editor Grasshopper, a pivotal tool within the iFOBOT system, is seamlessly integrated into the commercially available 3D modeling software Rhinoceros 3D ("Fologram," 2018) all visually depicted in Fig. 1.

- iFOBOT-environment module
  The iFOBOT-environment module aims to provide a comprehensive understanding of the construction site and its contextual factors. This involves the integration of Building Information Modeling (BIM) data and environmental parameters. The module's key steps include: (1) BIM integration: Importing the BIM model of the building project into the Grasshopper environment for subsequent analysis, (2) Environmental data incorporation: Introducing relevant environmental data, such as sun path analysis, weather conditions, and shading factors, to ensure accurate simulation outcomes, (3) Contextual analysis: Generating an iFOBOT-environment heat map that highlights areas of potential interest and impact on the construction site, (4) Data integration: Combining BIM and environmental data to create a comprehensive virtual representation of the construction site.
- iFOBOT-design module
  The iFOBOT-design module is responsible for generating optimal facade perforation designs based on defined criteria and constraints. The following steps outline its methodology: (1) Input parameters: Specifying parameters such as daylight requirements, thermal comfort thresholds, and LEED compliance criteria, (2) Facade perforation generation: Utilizing computational algorithms within Grasshopper to generate various facade perforation designs that meet the input parameters, (3) Heat map analysis: Employing the iFOBOT-environment heat map to evaluate the performance of each design in terms of daylight penetration and environmental impact, and (4) Optimization process: Iteratively refining the designs based on feedback from the heat map analysis to converge on an optimal perforation design.
- iFOBOT-construct module
  The iFOBOT-construct module translates the optimized design into physical construction actions through robotic

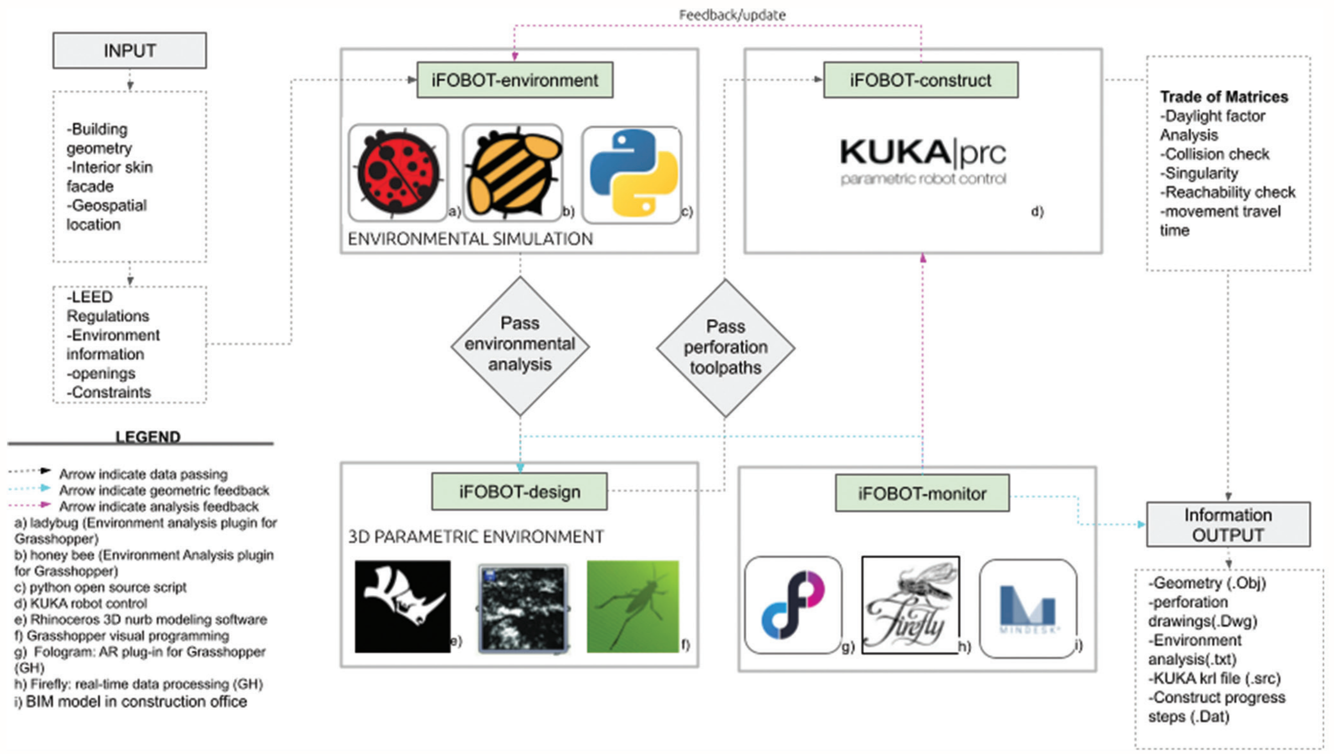

Fig. 1. The iFOBOT system's internal structure and the technique for transferring data between its many components.

perforation. The methodology comprises the following steps: (1) Geometry translation: Converting the finalized facade perforation design from the iFOBOT-design module into machine-readable commands for the robotic arm, (2) Robotic Path Planning: Developing a precise toolpath for the robotic arm to execute the perforation process efficiently and accurately, (3) real-time adjustment: Monitoring the robotic perforation process and making real-time adjustments based on environmental conditions and unforeseen obstacles, and (4) Quality assurance: Ensuring the quality and accuracy of the perforation process by validating the physical outcome against the digital design.

- iFOBOT-monitor module
  The iFOBOT-monitor module focuses on overseeing the robotic perforation process and facilitating communication between the construction site and the office. The methodology encompasses these steps: (1) Data acquisition: Capturing 3D point cloud data of the robotic perforation activity using a 3D camera, such as Kinect, (2) Data transformation: Converting the point cloud data into a 3D mesh representation for further analysis and inspection, (3) Data transmission: Transmitting the 3D mesh geometry from the construction site to the office for inspection and quality control, (4) Virtual reality inspection: Utilizing virtual reality interfaces, such as Oculus Rift, to enable inspectors to review and assess the as-built model in an immersive environment, and (5) Augmented reality feedback: Providing on-site workers with augmented reality feedback and reports for efficient communication and collaboration. Environment rule compliance and heat map generation (iFOBOT-environment Module)

The iFOBOT-environment module constitutes a sophisticated tool aimed at evaluating the adherence of facade designs to environmental regulations. Its primary function is to produce a heat map that identifies optimal areas for facade perforation, based on environmental considerations. Central to the iFOBOT-environment module's methodology is the meticulous evaluation of the annual solar exposure (ASE). This pivotal parameter serves as a cornerstone in assessing potential visual discomfort within the interior spaces of the building and contributes to determining the LEED v4 daylight credit. The approach involves constraining direct sunlight exposure beyond 1000 lux to no more than 250 h annually, ensuring it accounts for no less than 10% of the interior space ($ASE_{1000,250}$). This assessment operates at a specific work plane height of 750 mm above the finished floor, with the ASE grid size confined to dimensions below 600 mm^2 as visualized in Fig. 2.

The iFOBOT-construct module uses the KUKA|prc plugin ("KUKA|prc – parametric robot control for Grasshopper," 2011) to perform its tasks within the Grasshopper framework. This plugin enables the building of a parametric model for the trajectory of the robot arm as well as the production of a kinematic simulation of the robot's movements. Notably, the module creates 3D models of the workstation that include the robot arm, the outer facade wall, building limitations, and the perforation toolpath from the perforation process as shown in Fig. 3.

A. Augmented Reality and 3D Scanning Integration for Construction Oversight (iFOBOT-monitor)

Within the overarching iFOBOT framework, the iFOBOT-monitor module assumes a pivotal role in employing

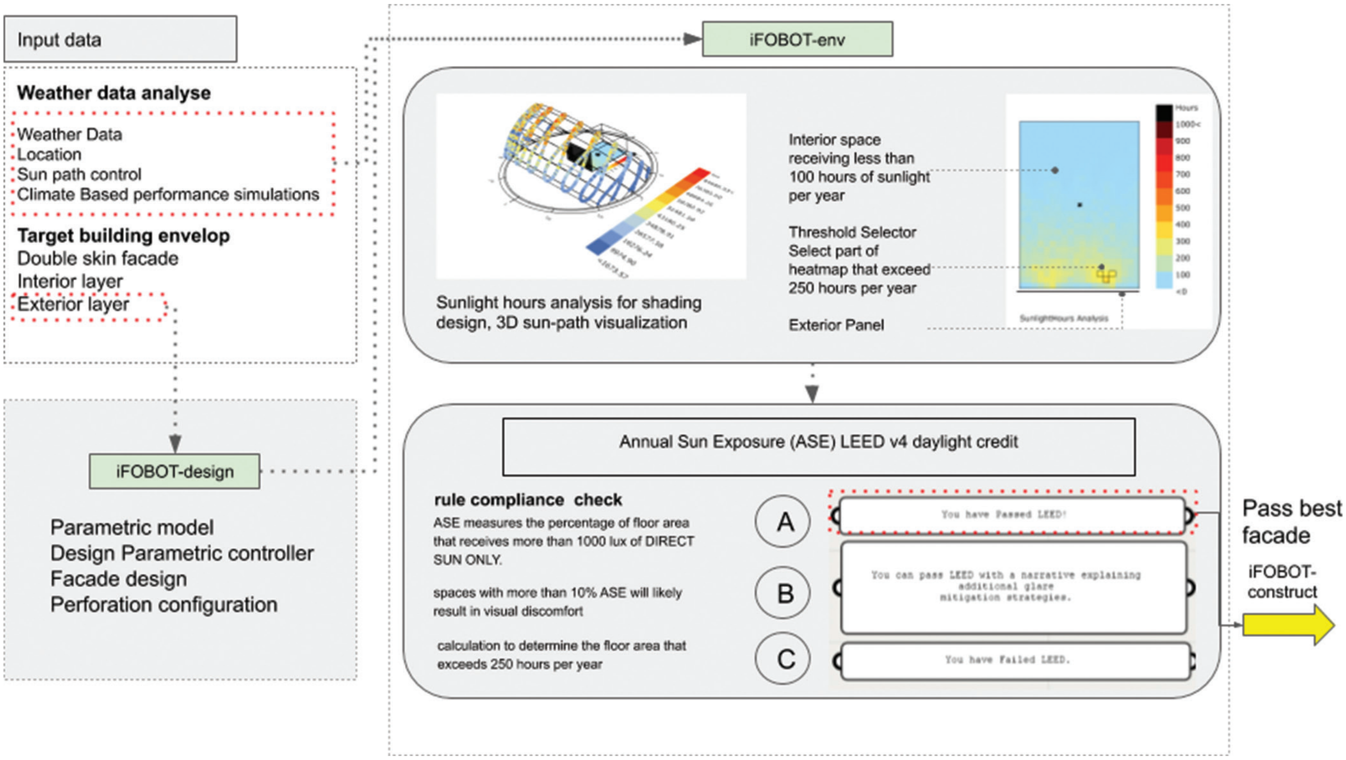

Fig. 2. Workflow and data interaction of iFOBOT-environment module with other modules.

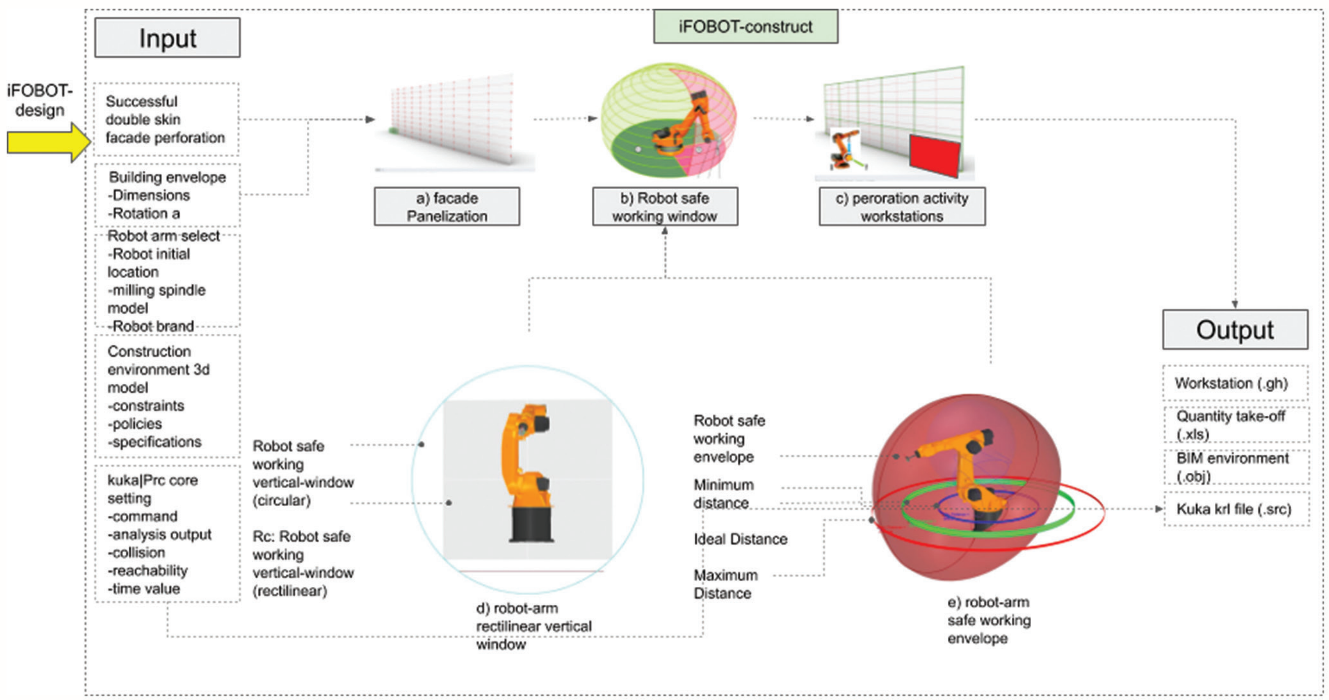

Fig. 3. Illustrates the workflow of the iFOBOT-construct module, focusing on robot simulation and the process of facade perforation.

augmented reality and 3D camera scanning to monitor the actions of the robotic arm within the construction site. Recognizing the dynamic and potentially hazardous nature of construction environments, the integration of a robust monitoring tool to capture and relay real-time data from the robotic arm's operations to the site office becomes indispensable during on-site perforation tasks. As a response to this imperative, the iFOBOT-monitor subsystem was seamlessly integrated into the broader iFOBOT system.

At its core, the iFOBOT-monitor strategy revolves around the continuous generation of 4D point clouds, achieved through the utilization of accessible and cost-effective on-site 3D scanning instruments, exemplified by the Kinect (Ali, Lee and Park, 2020a; Caruso, Russo and Savino, 2017; Weerasinghe, et al., 2012). At the construction job site (Location 1), the workflow commences with step 1, involving the utilization of a 3D LASER SCAN (c) employing the Xbox Kinect V2 laser scanning camera, connected to a dedicated computer (d). This initial step captures the physical environment in three dimensions, generating essential data for further analysis.

In step 2, this captured data undergoes a sequence of processing stages, encompassing POINT CLOUD MODELING. The process starts with Quokka (e), a tool for Kinect data processing within Grasshopper (GH), followed by real-time data processing facilitated by Firefly (f) within the Grasshopper environment. Tarsier (g) is then employed for point cloud management, and Speckle (h) handles real-time broadcasting of the collected data. Additionally, a 3D PARAMETRIC ENVIRONMENT (i) is established using Grasshopper, a graphical algorithm editor. Within this, step 3, engineers have the capability to remotely inspect the construction site from their office, facilitated by the Mindesk library integrated into Grasshopper (i). Rhinoceros (j), a 3D Nurbs modeling software, plays a pivotal role by converting the point cloud data from (i) into 3D geometry and subsequently feeds it into (i) for viewing in virtual reality. The building information modeling (BIM) model, represented in (k), serves as a crucial reference point in the construction office.

Finally, in Step 4, feedback is relayed to the workers on the job site. This feedback process is facilitated through the deployment of Fologram (a), an augmented reality plug-in integrated within Grasshopper (GH). Workers on the construction site receive this feedback on their smartphones (b). The feedback is presented in multiple layers, comprising the BIM model, a point cloud, and a BIM overlay model, as well as notes and drawings, providing a comprehensive and real-time insight into the project's status as shown in Fig. 4.

IV. CASE STUDY

This section outlines the fundamental setup of the thermal model. It adopts a single-zone layout, representing a solitary room within a larger structure while treating the glass façade as non-adiabatic. Various shading techniques were applied to the model's external surfaces to facilitate comprehensive simulations of thermal properties, daylighting, and glare. The specific case study took place at the address 471-080 Galmae-dong Guri-si, Gyeonggi-do Seoul, South Korea, as depicted in Fig. 5.

Exploring the effectiveness of conventional shading strategies under stringent constraints involved an examination of four distinct facade design alternatives. The

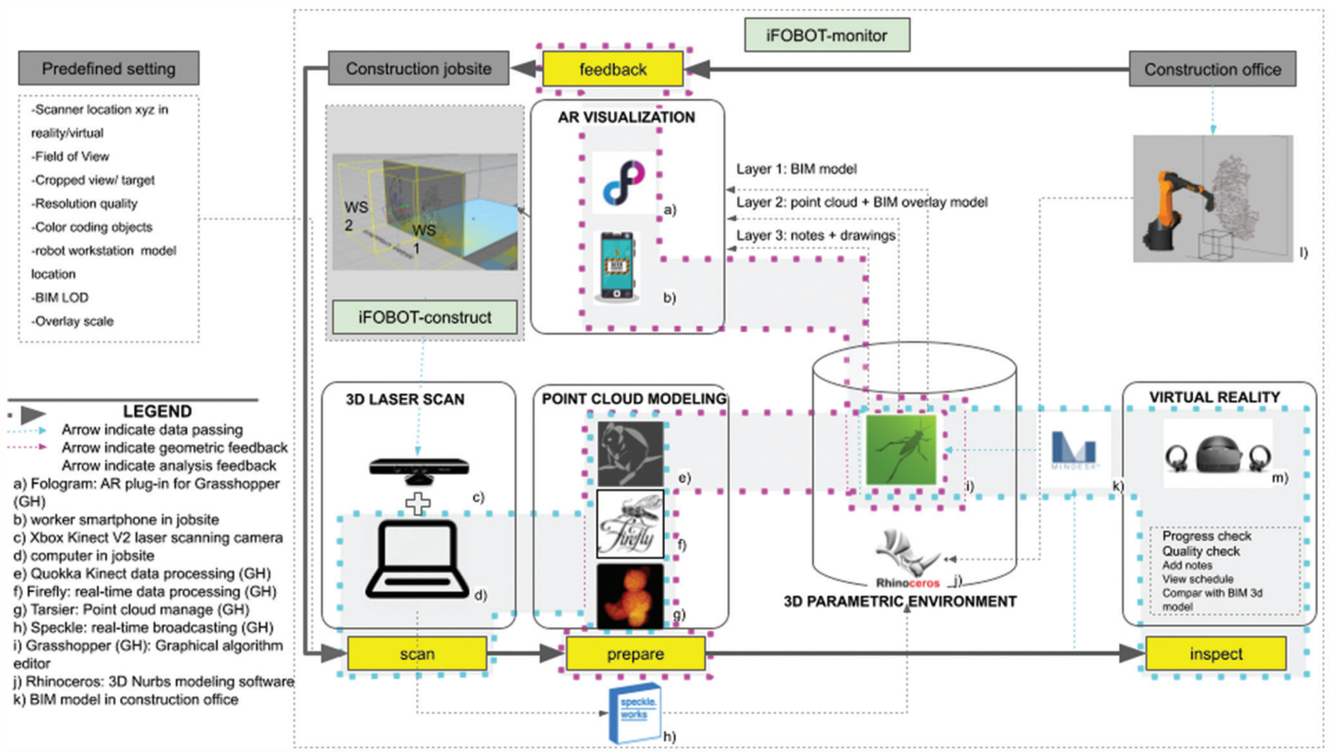

Fig. 4. The iFOBOT-monitor module utilizes 3D laser scanning and extended reality technologies for visual progress assessment.

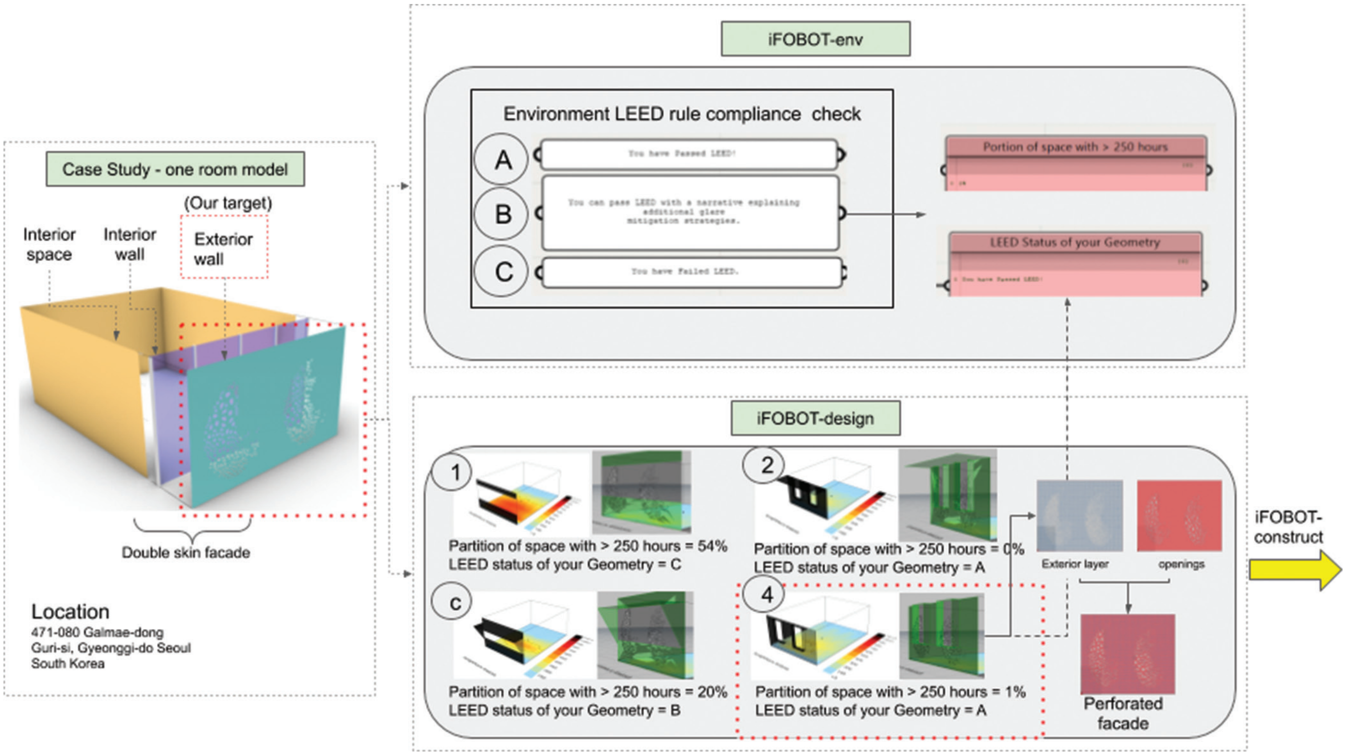

Fig. 5. Illustration of iFOBOT environment and design tool in a building's single room case study.

iFOBOT process was initiated by simulating these exterior configurations within the iFOBOT-environment, focusing on areas exposed to over 250 h of daylight and evaluating their compliance with LEED standards.

The initial design encompassed a partition of space with daylight exposure exceeding 250 h, accounting for 54% of the area; however, it did not meet LEED v4 requirements. In contrast, the second design achieved a partition with no daylight exposure beyond 250 h, aligning with LEED v4 criteria. The third design featured a partition of space with over 250 h of daylight, constituting 20% of the area, with a Geometry classification of "B" according to LEED standards. The fourth design achieved a partition with only 1% of the space exposed to more than 250 h of daylight and successfully complied with the LEED v4 index. These distinct facade designs are visually depicted in Fig. 5, labeled as designs 1, 2, 3, and 4.

The integration of the model into the Rhino simulation environment facilitated an understanding of how building constraints impact the shading system's efficiency. This iterative feedback process informed the generation of robotic code for subsequent production, resulting in a comprehensive study that harmonized design performance and constraints. The case study is presented in a series of steps:

1. Initial Setup and Design Conceptualization:
   - Define the scope of the case study, focusing on the design and robotic fabrication of a double-skin facade system
   - Develop the preliminary design concepts for the double-skin facade, considering architectural esthetics and environmental performance
   - Identify the facade's perforation requirements and its alignment with the LEED v4 daylighting index.
2. iFOBOT-Environment Simulation:
   - Utilize the iFOBOT-environment module to simulate the environmental performance of various facade perforation configurations
   - Generate heat maps and daylighting simulations to assess the impact of different perforation patterns on interior illumination levels and energy efficiency.
3. iFOBOT-Design and Optimization:
   - Employ the iFOBOT-design module to translate the environmental simulation results into specific perforation designs
   - Utilize parametric modeling tools to generate intricate and visually appealing facade perforation patterns while meeting the LEED v4 criteria.
4. Robotic Path Generation and Simulation:
   - Implement the iFOBOT-construct module to generate robotic toolpath trajectories for on-site perforation using a 6-axis robotic arm
   - Simulate the robotic path and verify its accuracy in a virtual environment, considering factors such as material thickness and fabrication constraints.
5. On-Site Robotic Perforation:
   - Deploy the generated robotic toolpath on the actual construction site using a KUKA HA 30/60 robotic arm
   - Monitor the robotic perforation process, ensuring alignment with the pre-simulated path and precise execution of perforations.
6. Data Capture and iFOBOT-Monitor Integration:
   - Employ the iFOBOT-monitor module to capture 3D point cloud data of the perforation process using a Kinect V2 camera
   - Convert the captured point cloud data into a 3D mesh representation and transmit it to the construction office for inspection.
7. Virtual Reality Inspection and Feedback:
   - Utilize augmented reality technologies and the iFOBOT-monitor module to conduct a virtual reality inspection of the as-built facade
   - Enable inspectors to review the perforation quality, make annotations, and assess adherence to design specifications.
8. Evaluation and Comparison:
   - Evaluate the performance and effectiveness of the robotic fabrication process based on the physical outcome and the alignment with design intent
   - Compare the as-built facade with the initial design and simulation results, highlighting areas of success and potential improvements.
9. Iterative Refinement and Future Considerations:
   - Use the insights gained from the case study to refine and optimize the iFOBOT workflow for future projects
   - Consider the integration of outdoor depth sensing sensors for improved data capture in outdoor environments.
10. Conclusion and Contribution:
    - Summarize the case study findings, emphasizing the efficacy of the integrated iFOBOT workflow in achieving a harmonious synergy between design and robotic fabrication
    - Highlight the broader implications of the study's contribution to the field of architecture, automation, and sustainable design.

By following these steps, the case study effectively demonstrates the practical application and benefits of the iFOBOT platform in the context of designing and fabricating a double-skin facade system

A. Verification of iFOBOT-environment and iFOBOT-design through a Practical Case Study

In the pursuit of validating the efficacy of iFOBOT-environment and iFOBOT-design, a comprehensive case study was undertaken. Leveraging the capabilities of the Grasshopper framework, the iFOBOT-design module employed an image collection tool to generate perforations aligned with the initial facade openings. This process was guided by the heat map derived from the optimal facade design, designated as Façade Design 4 for this analysis. The resulting perforated facade apertures seamlessly transitioned from iFOBOT-design and iFOBOT-environment to the iFOBOT-construct module, facilitating a streamlined on-site construction process, as visually demonstrated in Fig. 5.

B. Case Study for iFOBOT Construct Validation

The validation process for iFOBOT-construct involved the utilization of a commercial 6-axis KUKA HA 30/60 robotic arm for the intricate perforation task. Employing a systematic approach, a series of specialized Grasshopper definitions was meticulously crafted to translate the meticulously optimized geometry positioning commands from earlier stages. This painstaking calibration ensured the attainment of stringent tolerances, further enhancing the quality and accuracy of the perforation process. Moreover, the enhanced manufacturing process incorporated robotic post-processing in its raw state, guaranteeing uniform thickness and meticulous shaping of components, thereby culminating in a cohesive and exacting outcome, as vividly depicted in Fig. 6.

C. Case Study Validating iFOBOT-Monitor: Monitoring and Data Exchange Workflow

This case study scrutinizes the effectiveness of iFOBOT-monitor in supervising perforation activities and delivering real-time updates to the construction office. The module's operation commences with the acquisition of 3D point cloud data through a comprehensive scene scan conducted by a 3D camera. Subsequent to data collection, a transformation process ensues, transitioning from point cloud modeling to the creation of a 3D mesh representation.

The pivotal role of the iFOBOT-monitor module within the iFOBOT framework becomes evident through its efficient and rapid data exchange between the project site and the construction office. Integration of diverse technologies onto a single platform facilitates seamless communication, exemplified by an average 17-min data exchange cycle. Visual comparison between the digital model and the job site point cloud offers a definitive means of assessing the accuracy of robotic movements and perforation processes, as demonstrated in Fig. 7.

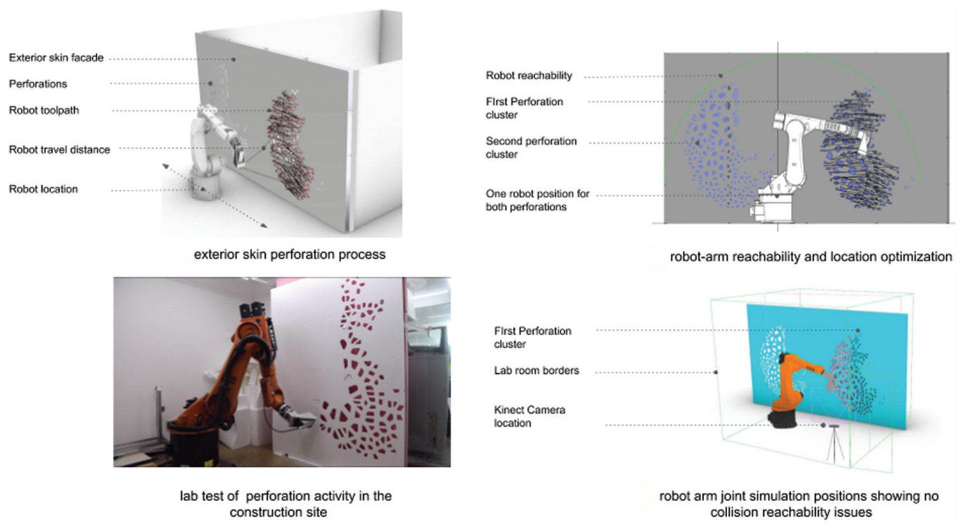

Fig. 6. Implementation of perforation process at the construction site utilizing robotic arm technology.

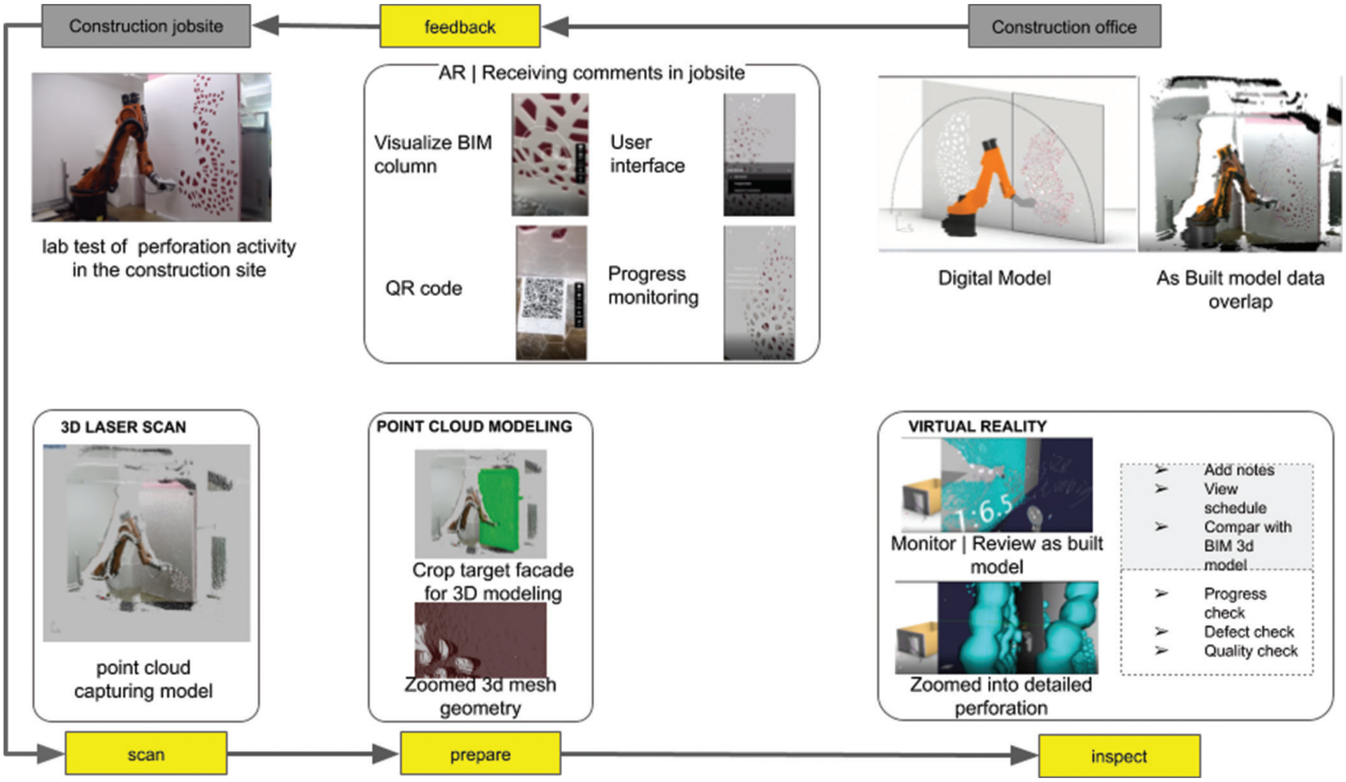

Fig. 7. The case study for the iFOBOT-monitor module involves the examination of point cloud generation and the utilization of extended reality technologies.

In the iFOBOT-monitor module's "Inspect" phase, virtual reality functionalities are facilitated through the Mindesk library, enabling remote inspection by engineers situated in the office. In the ensuing "Feedback" stage, the worker leverages augmented reality technology managed by the Fologram library within the iFOBOT-monitor module. Here, the worker can: employ QR codes to superimpose the digital model onto the actual wall; access comments provided by the inspector; and explore the BIM digital model through layered visualization. The amalgamation of mixed reality technologies enhances visual communication between the office and the construction site throughout the construction process as shown in Fig. 8.

This research provides a comprehensive depiction of the quantifiable workflow and the corresponding advantages realized during the validation of iFOBOT-Monitor in Case Study C. Quantitative metrics within the table highlight the average duration of data exchange between the construction site and office, effectively showcasing the remarkable efficiency gains achieved. Furthermore, the table underscores the module's intrinsic capability to visually assess the precision of robotic movements and the accuracy of the perforation process by superimposing the digital model onto the point cloud. This detailed analysis underscores the robustness and efficacy of iFOBOT-monitor in enhancing and optimizing construction procedures as shown in Table II.

V. Discussion

This study introduces an enhanced iFOBOT system, specifically tailored for the on-site perforation of dual skin surfaces, and provides a comprehensive assessment of its capabilities. The case study elucidated the profound influence of design parameters and perforation angles on design evolution and system dynamics. The precision of perforation scale and arrangement within the double skin façade is effectively regulated through the intricate interplay between iFOBOT-design and iFOBOT-environment, ensuring adherence to the LEED v4 index criteria. Empirical trials

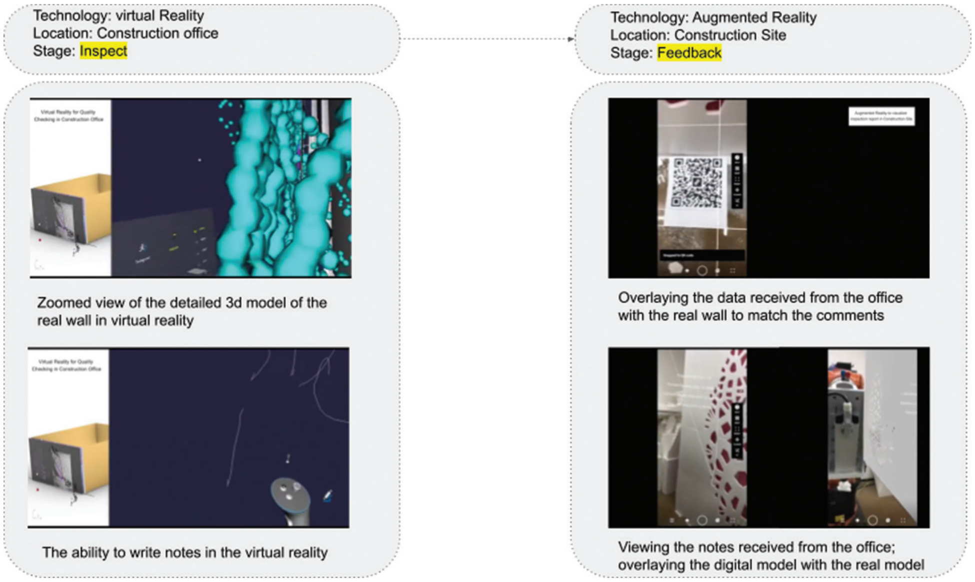

Fig. 8. Virtual reality and augmented reality technology tools are used in the inspection and feedback section.

TABLE II
The Information Presented in a Quantifiable Table Format

Case Study C: iFOBOT-Monitor Validation	
Monitoring and Data Exchange Workflow	
Step	Average time (min)
Acquisition of 3D Point Cloud Data	12
Point Cloud to 3D Mesh Transformation	5
Data Transmission to Construction Office	2
Virtual Reality Inspection and Report Generation	10
Feedback Report Communication to On-site Worker	5
Data Exchange Cycle	Average: 17
Benefits and Outcomes	
Real-time Monitoring and Reporting	Efficient oversight of perforation operations and instant status updates
Data Exchange Efficiency	Rapid data exchange between the project site and construction office
Visual Inspection in Virtual Reality	Detailed assessment and annotation of the as-built model
Accuracy Assessment	Comparison of digital model and job site point cloud for precise evaluation

yielded promising outcomes, with approximately 1.5 h expended to complete half of the perforation task.

While the Kinect camera employed in this study demonstrated optimal performance within controlled indoor lighting environments, its efficacy is constrained when deployed outdoors. As a future enhancement, we envisage the integration of outdoor depth sensing sensors such as ZED 2 ("ZED 2 – AI Stereo Camera | Stereolabs," n.d.) into the iFOBOT system, catering to a broader range of environmental conditions. Furthermore, data collection and assessment will be pursued to refine the heuristic methodology and facilitate module optimization. The seamless integration of geometry and data flow throughout the various iFOBOT modules remains a focal point for future endeavors. Enhancing dataflow to incorporate essential feedback gleaned from building inputs and simulations represents a pivotal stride toward fortifying the efficacy of the iFOBOT framework as illustrated in Table III.

Finally, the iFOBOT-monitor module plays a pivotal role in real-time oversight and management of the perforation process. Facilitating remote monitoring and data collection, this module ensures quality control and collaboration between on-site teams and the construction office. Its real-time insights provide numerous benefits, allowing for timely adjustments, quality assessments, and effective issue resolution. However, the module's efficacy may be contingent on stable communication networks and robust data acquisition, with potential limitations arising from data quality and resolution as shown in Table IV.

To comprehensively evaluate the performance and usability of the iFOBOT platform and its individual modules, a thorough assessment was conducted involving 30 experienced engineers from diverse backgrounds. In the assessment process, each module (iFOBOT-environment, iFOBOT-design, iFOBOT-construct, iFOBOT-monitor) and the iFOBOT platform as a whole are evaluated based on various survey questions. Engineers provide their rankings on a scale of 1–5, with 1 being the lowest and 5 being the highest satisfaction level. The table provides an overview of the survey results, allowing for a quick comparison of the user evaluation for each module and the overall platform as shown in Table V.

TABLE III
Comparison of iFOBOT with Other Platforms and Previous Research

Aspect	iFOBOT	Platform A (Kim, Konstantzos and Tzempelikos, 2007)	Platform B (Keating and Oxman, 2013)	Platform C (Kim, Konstantzos and Tzempelikos, 2020)
Perforation Task	On-site dual skin perforation with augmented reality feedback and monitoring	Exterior facade perforation with digital simulation and visualization	Robotic fabrication of building envelope using the multi-axis robotic arm	Single-layer facade perforation with low-cost robotic manipulation
Design Integration	Integrating design, simulation, and production processes in a seamless manner on a single platform	One software environment for the design and manufacturing processes	Separate design and fabrication processes	Integrated design and fabrication processes within a single platform
Robotic Arm Capability	6-axis KUKA HA 30/60 with efficient tool path generation and perforation control	4-axis robotic arm with limited tool path generation and perforation control	Multi-axis robotic arm with adaptable tool path generation and control	Multi-axis robotic arm with adaptable tool path generation and control
Data Exchange	Rapid and efficient data exchange between design, fabrication, and construction processes	Limited data exchange between design and fabrication processes	Data exchange with remote operation site and construction processes	Real-time data exchange and monitoring capabilities
Strengths	Real-time monitoring with augmented reality feedback, seamless design integration, rapid data exchange, and efficient robotic perforation control	Efficient design and fabrication processes within a unified environment	Multi-axis robotic arm with adaptable tool path generation and control	Integration of design, simulation, fabrication, and monitoring processes within a single platform
Weaknesses	Limited outdoor use, potential camera limitations, manual adjustments for optimal scanning	Limited capabilities for complex designs, limited tool path generation, no augmented reality feedback	Limited adaptability to varying designs, limited structural adaptability	Limited adaptability to complex designs, limited tool path generation, no real-time monitoring

TABLE IV
Comparison of Objectives, Benefits, and Limitations of iFOBOT Modules

iFOBOT Module	Objectives	Benefits	Limitations
iFOBOT-environment	Create an integrated digital workspace for architectural designs with environmental considerations	Real-time feedback, informed design decisions, performance metrics	Environmental simulation accuracy influenced by input data
iFOBOT-design	Automate facade design generation adhering to performance criteria	Efficient design exploration, streamlined decision-making	Potential constraints in addressing esthetics and complexities
iFOBOT-construct	Generate precise robotic tool paths and control commands for on-site fabrication	Enhanced fabrication accuracy, error minimization	Calibration and environmental variations affecting accuracy
iFOBOT-monitor	Provide real-time oversight and data management for perforation operations	Quality control, remote collaboration, timely adjustments	Dependence on stable communication, data quality, and resolution

TABLE V
User Assessment Results for iFOBOT Modules

Survey Question	iFOBOT-Environment	iFOBOT-Design	iFOBOT-Construct	iFOBOT-Monitor	iFOBOT Platform
Interface design	4.3	4.1	3.9	4.2	4.1
System flexibility	3.9	4.2	3.7	4.0	4.0
User friendliness	4.2	4.3	3.8	4.1	4.1
Learning curve	4.0	4.2	3.6	4.0	4.0
Efficiency in design process	4.1	4.3	3.8	4.2	4.1
Precision of generated design	3.8	4.2	3.9	4.1	4.0
Integration with existing software/tools	4.0	4.1	3.9	4.2	4.1
Real-time data exchange	4.1	4.0	3.7	4.3	4.1
Monitoring accuracy	3.9	4.0	3.8	4.2	4.0
Data visualization quality	4.2	4.3	3.9	4.1	4.1
Overall user satisfaction	4.1	4.2	3.8	4.2	4.1

The assessment outcomes from 30 engineers provide valuable insights into the usability and effectiveness of each iFOBOT module. Notably, iFOBOT-environment received high praise for its intuitive interface and efficient parameter input, resulting in an average ranking of 4.6 out of 5. iFOBOT-design, though positively received (average ranking of 4.3), was noted for a slight learning curve, suggesting the need for improved guidance. iFOBOT-construct, with an average ranking of 4.5, impressed users with its ability to generate accurate milling paths for robotic arms.

In conclusion, the comprehensive user assessment of the iFOBOT platform, involving a diverse group of 30 engineers, has provided valuable insights into the practical usability and effectiveness of each module. The obtained rankings, ranging from 1 (Low) to 5 (High), offer a quantifiable measure of the user experience, ease of use, and perceived benefits of the iFOBOT-environment, iFOBOT-design, iFOBOT-construct, and iFOBOT-monitor modules. The overall positive feedback indicates that the platform holds significant promise for enhancing efficiency and precision in robotic-assisted construction tasks. This assessment serves as a crucial step in validating the real-world applicability and user-centric design of the iFOBOT system, paving the way for further refinements and broader adoption in the construction industry.

VI. Conclusion

This study introduces a comprehensive and integrated methodology for robotic manufacturing, showcasing its adaptability to diverse material systems. Although specifically tailored to a high-performance ceramic facade system, the proposed framework demonstrates its potential applicability across various architectural contexts. The consolidation of crucial operations within a unified software framework, facilitated by custom Grasshopper scripts and components, serves as a catalyst for enhanced collaboration among key stakeholders involved in conceiving specialized and high-performance facade designs. Moreover, the automated workflow streamlines the production process, allowing for iterative exploration of building geometry and validation of its alignment with design intent during the early design phases.

Environmental optimization emerges as a pivotal contributor, enabling the generation of highly customized facade patterns that exhibit both complexity and esthetic appeal. The pragmatic dimension of this approach transcends performance-driven objectives, responding to a growing interest in meticulous parametric design representations that foster demand for optimization in their own right. The fusion of intricate geometries with established manufacturing practices, underpinned by digital design methodologies, underscores the feasibility of translating diverse design visions into tangible architectural realities.

Within the discourse of architectural discourse, the perpetual dichotomy between cost-effective, high-volume industrial manufacturing and bespoke, design-driven architecture has been an ongoing deliberation. This study suggests that the convergence of robotic technologies and design automation presents a potential reconciliation, offering a compelling third perspective. The coexistence of these attributes underscores that prioritizing environmental efficiency as a guiding principle need not eclipse the fundamental essence of architectural creativity. This synthesis of technological advancement and artistic expression opens avenues for design solutions that resonate with both economic considerations and design aspirations, thus contributing to the evolution of architectural practice.

References

Abbasnejad, B., Nepal, M.P., Ahankoob, A., Nasirian, A., and Drogemuller, R., 2021. Building Information Modelling (BIM) adoption and implementation enablers in AEC firms: A systematic literature review. *Architectural Engineering and Design Management*, 17, pp.411-433.

Ali, A.K., Lee, O.J., and Park, C., 2020a. Near real-time monitoring of construction progress: Integration of extended reality and kinect V2. In: *Proceedings of the International Symposium on Automation and Robotics in Construction*. IAARC Publications, pp.24-31.

Ali, A.K., Lee, O.J., and Song, H., 2020b. Generic design aided robotically facade pick and place in construction site dataset. *Data in Brief*, 31, p.105933.

Ali, A.K., Lee, O.J., and Song, H., 2021. Robot-based facade spatial assembly optimization. *Journal of Building Engineering*, 33, p.101556.

Babatunde, S.O., Ekundayo, D., Adekunle, A.O., and Bello, W., 2020. Comparative analysis of drivers to BIM adoption among AEC firms in developing countries: A case of Nigeria. *Journal of Engineering Design and Technology*, 18, pp.1425-1447.

Bosché, F., Guillemet, A., Turkan, Y., Haas, C.T., and Haas, R., 2014. Tracking the built status of MEP works: Assessing the value of a Scan-vs-BIM system. *Journal of Computing in Civil Engineering*, 28, p.05014004.

Caruso, L., Russo, R., and Savino, S., 2017. Microsoft Kinect V2 vision system in a manufacturing application. *Robotics and Computer-Integrated Manufacturing*, 48, pp.174-181.

Fologram, 2018. Food4Rhino. Available from: https://www.food4rhino.com/en/app/fologram [Last accessed on 2023 Aug 14].

Hashemi, M., 2021. *Human-Robot Collaborative Design (HRCoD): Real-Time Collaborative Cyber-Physical HMI Platform for Robotic Design and Assembly through Augmented Reality* (PhD Thesis). Kent State University.

Hook, J., 2016. *Automated Digital Fabrication Concept for Composite Facades.* Honours Thesis. The University of Queensland.

Jenny, S.E., Pietrasik, L.L., Sounigo, E., Tsai, P.H., Gramazio, F., Kohler, M., Lloret-Fritschi, E., and Hutter, M., 2023. Continuous mobile thin-layer on-site printing. *Automation in Construction*, 146, p.104634.

Keating, S., and Oxman, N., 2013. Compound fabrication: A multi-functional robotic platform for digital design and fabrication. *Robotics and Computer-Integrated Manufacturing*, 29, pp.439-448.

Keating, S.J., Leland, J.C., Cai, L., and Oxman, N., 2017. Toward site-specific and self-sufficient robotic fabrication on architectural scales. *Science Robotics*, 2, p.eaam8986.

Kim, M., Konstantzos, I., and Tzempelikos, A., 2020. Real-time daylight glare control using a low-cost, window-mounted HDRI sensor. *Building and Environment*, 177, p.106912.

Kim, Y.S., Jung, M.H., Cho, Y.K., Lee, J., and Jung, U., 2007. Conceptual design and feasibility analyses of a robotic system for automated exterior wall painting. *International Journal of Advanced Robotic Systems*, 4, p.49.

Kontovourkis, O., Tryfonos, G., and Georgiou, C., 2020. Robotic additive manufacturing (RAM) with clay using topology optimization principles for toolpath planning: The example of a building element. *Architectural Science Review*, 63, pp.105-118.

Krieg, O.D., 2022. *Architectural Potentials of Robotic Manufacturing in Timber Construction: Strategies for Interdisciplinary Innovation in Manufacturing and Design*. Institute for Computational Design and Construction, University, Stuttgart.

KUKA. Prc- Parametric Robot Control for Grasshopper, 2011. Food4Rhino. Available from: https://www.food4rhino.com/en/app/kukaprc-parametric-robot-control-grasshopper [Last accessed on 2023 Aug 14].

Kurtser, P., Ringdahl, O., Rotstein, N., Berenstein, R., and Edan, Y., 2020. In-field grape cluster size assessment for vine yield estimation using a mobile robot and a consumer level RGB-D camera. *IEEE Robotics and Automation Letters*, 5, pp.2031-2038.

Kwon, O.S., Park, C.S., and Lim, C.R., 2014. A defect management system for reinforced concrete work utilizing BIM, image-matching and augmented reality. *Automation in Construction*, 46, pp.74-81.

Park, C.S., Lee, D.Y., Kwon, O.S., and Wang, X., 2013. A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template. *Automation in Construction*, 33, pp.61-71.

Rahimian, F.P., Seyedzadeh, S., Oliver, S., Rodriguez, S., and Dawood, N., 2020. On-demand monitoring of construction projects through a game-like hybrid application of BIM and machine learning. *Automation in Construction*, 110, p.103012.

Rea, P., and Ottaviano, E., 2018. Design and development of an inspection robotic system for indoor applications. *Robotics and Computer-Integrated Manufacturing*, 49, pp.143-151.

Rebolj, D., Pučko, Z., Babič, N.Č., Bizjak, M., and Mongus, D., 2017. Point cloud quality requirements for Scan-vs-BIM based automated construction progress monitoring. *Automation in Construction*, 84, pp.323-334.

Weerasinghe, I.T., Ruwanpura, J.Y., Boyd, J.E., and Habib, A.F., 2012. Application of Microsoft Kinect sensor for tracking construction workers. In: *Construction Research Congress 2012: Construction Challenges in a Flat World*. American Society of Civil Engineers, Reston, pp.858-867.

Willmann, J., Knauss, M., Bonwetsch, T., Apolinarska, A.A., Gramazio, F., and Kohler, M., 2016. Robotic timber construction-Expanding additive fabrication to new dimensions. *Automation in Construction*, 61, pp.16-23.

Yang, D., Li, Y., Li, T., Zhang, T., Han, M., and Yan, H., 2020. The system design of external cladding installation robot. *International Journal of Advanced Robotic Systems*, 17.

ZED 2 - AI Stereo Camera, n.d. Stereolabs. Available from: https://www.stereolabs.com/zed-2 [Last accessed on 2023 Aug 14].

Zied, K., 2007. An augmented framework for practical development of construction robots. *International Journal of Advanced Robotic Systems*, 4, p.43.