RoboSense

Context-Dependent Robotic Design Protocols and Tools

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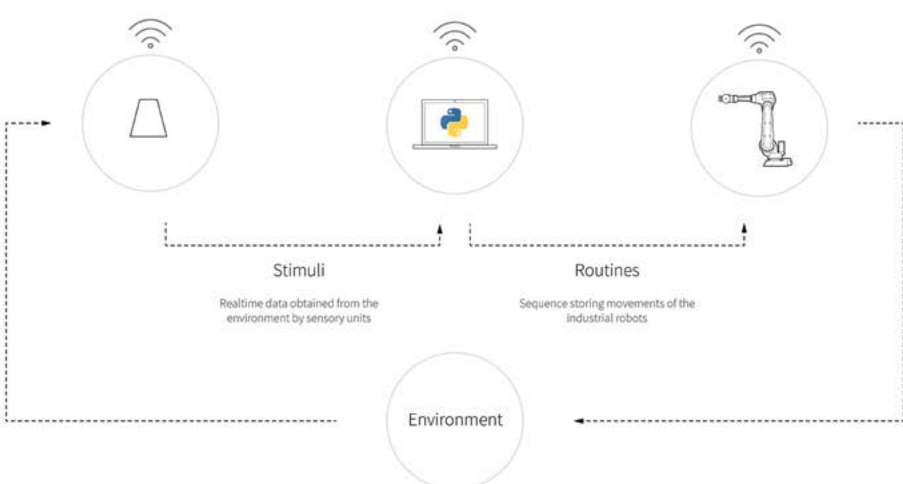

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1 Pipeline for coordination of information exchange between sensory units, control center and effector units.

ABSTRACT

While nonlinear concepts are widely applied in analysis and generative design in architecture, they have not yet convincingly translated into the material realm of fabrication and construction. As the gap between digital design model, shop drawing, and fabricated result continues to diminish, we seek to learn from fabrication models and natural systems that do not separate code, geometry, pattern, material compliance, communication, and form, but rather operate within dynamic loops of feedback, reciprocity, and generative fabrication. Three distinct, but connected problems: 1) Robotic ink drawing; 2) Robotic wine pouring and object detection; and 3) Dynamically Adjusted Extrusion; were addressed to develop a toolkit including software, custom digital design tools, and hardware for robotic fabrication and user interaction in cyber-physical contexts. Our primary aim is to simplify and consolidate the multiple platforms necessary to construct feedback networks for robotic fabrication into a central and intuitive programming environment for both the advanced to novice user. Our experimentation in prototyping feedback networks for use with robotics in design practice suggests that the application of this knowledge often follows a remarkably consistent profile. By exploiting these redundancies, we developed a support toolkit of data structures and routines that provide simple integrated software for the user-friendly programming of commonly used roles and functionalities in dynamic robotic fabrication, thus promoting a methodology of feedback-oriented design processes.

INTRODUCTION

Recent advances in computation, visualization, material intelligence, and fabrication technologies have begun to fundamentally alter our theoretical understanding of general design principles as well as our practical approach towards architecture and research. This renewed interest in complexity has offered alternative methods for investigating the interrelationships of parts to their wholes, and emergent self-organized material systems at multiple scales and applications. The advantages of researching and deploying such methodologies in the field of architecture are huge, as they impact aspects of sustainable design, optimization, construction, and novel design expression and material systems.

Existing digital fabrication techniques such as CNC (computer numerically controlled) milling and cutting are useful tools, but they are also severely limited by their 2D and reductive constraints. 3D CNC tools offer a much more adequate and versatile approach to issues of shape, material, and geometry, but these tools are particularly underexplored when it comes to fabrication at the architectural scale. Two of the most promising technologies are 3D printing and rapid assembly via robotics for manufacturing of individual and continuous component parts or fibrous assemblages, skin systems, and nonstandard architectural elements. Together, these technologies are geared towards becoming indispensable tools for nonlinear manufacturing as well as complex form-making, but they raise the question: How might advancements in robotic fabrication and design in alternate industries and disciplines impact the architectural design process? Needed now are rigorous multi-directional and multi-disciplinary investigations that can help shape the future trajectories of these material innovations and technologies for architecture.

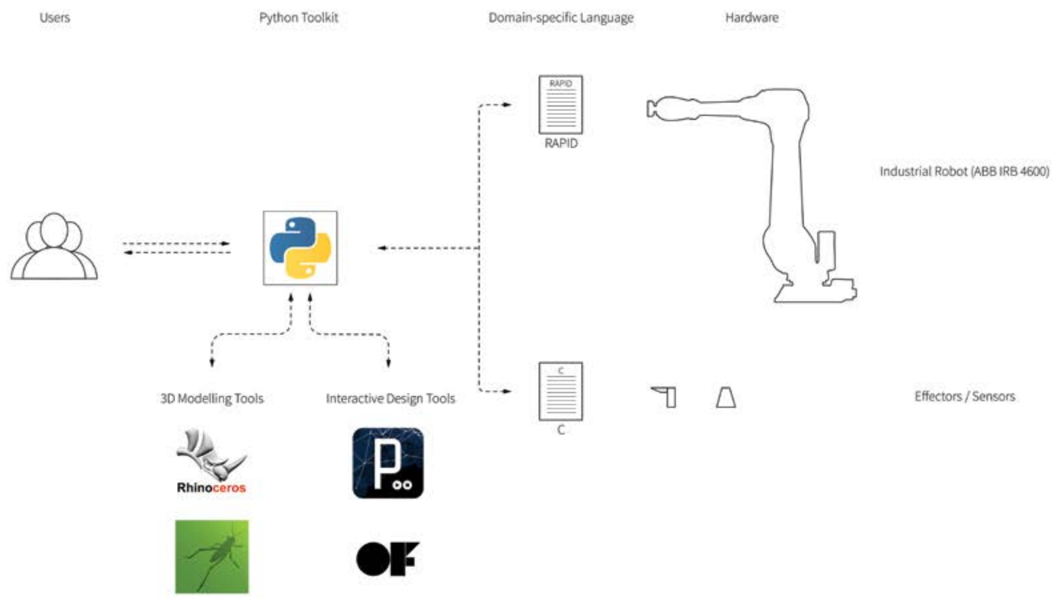
This paper focuses on one area of ongoing design research in the Sabin Design Lab at Cornell AAP: the development of novel custom-design tools and interfaces featuring environmental feedback for user interaction with a 6-axis industrial robot. Our goal is two-fold: 1) The design and implementation of a user friendly pipeline and interface for the seamless programming of an ABB IRB 4600 45 kg, 2.05 m reach industrial robot to operate in concert with cyber-physical devices; and 2) To develop a flexible tool kit that will foster a design process and methodology enmeshed in feedback, and will engage the human hand and digital handcraft in the co-production of robotically steered materiality and novel tectonic systems.

BACKGROUND

The Sabin Design Lab at Cornell AAP is an experimental design research lab that investigates the intersections of architecture and science, and applies insights and theories from biology, physics, engineering, computer science, and mathematics to the design of material structures. We ask, “How might architecture respond to issues of ecology and sustainability whereby buildings behave more like organisms in their built environments? What role do humans play in response to changing conditions within the built environment?” The Sabin Design Lab is interested in probing the human body for design models that give rise to new ways of thinking about issues of adaptation, change, and performance in architecture. Our research projects are diverse and operate across multiple scales from the nano to the macro. The Sabin Design Lab specializes in computational design, data visualization, and digital fabrication.

There are now certainly many established and internationally recognized research and design units engaged in these topics and questions, including the Mediated Matter Group at MIT led by Neri Oxman; the Self-Assembly Lab at MIT led by Skylar Tibbits; and CITA at the Royal Danish Academy of Fine Arts led by Mette Ramsgaard Thomsen. Several cutting-edge research units are advancing this type of work primarily as it touches upon issues of construction, fabrication, and large-scale architectural applications, including pavilions, walls, and envelopes. The work of Achim Menges and his students at the Institute for Computational Design (ICD) at University of Stuttgart operates at a large scale through the explicit exploration of natural systems for novel structures in the context of computational matter. Recently, the ICD and the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart have constructed a biomimetic fiber-reinforced polymer (FRP) research pavilion, whose building method accommodates changing stiffness in a pneumatic formwork for robotic fiber placement through an integrated sensor for toolpath-adjustment based on contact force with the formwork. Designed, fabricated, and constructed over one-and-a-half years by students and researchers within a multi-disciplinary team of biologists, paleontologists, architects, and engineers, this project investigates natural fiber composite shells alongside the development of cutting-edge robotic fabrication methods for FRP structures (Menges and Knippers 2015; Vasey et al. 2015).

Similarly, Gramazio and Kohler of ETH Zurich focus on additive digital fabrication techniques used for building non-standardized architectural components including bricks, mesh structures and smart dynamic casting with concrete and other plastic materials. One such investigation into Remote Material Deposition (RMD) studied adaptation to changing construction conditions for assembling structures with thrown clay, using digital point cloud data to adjust tool-paths based on material divergences due to the clay’s malleability and the unpredictability in landing conditions (Dörfler et al. 2014).



2 Python toolkit allowing users to auto generate rapid code for programming contextually informed robotic tool paths through user-friendly interfaces.

While both of these exemplary research units engage similar trajectories in non-standard dynamic robotic manufacturing, we are also invested in design processes that employ the human hand, personalization, and even empathy. Closer to this is the work of Guy Hoffman, who is at the forefront of human-robot interaction that engages joint activities between humans and robots and human-robot collaboration (Hoffman 2004).

In each case, a simultaneous transition in design methodology occurs by shifting the production machine from the executor of an explicit and comprehensive set of commands to an actor in a dynamic and reciprocal relationship with its fabrication environment. This is evident in recent architectural research that incorporates moments of feedback in online robotic fabrication processes. However, little elucidation is provided on the complexity inherent in programming these dynamic feedback networks, and few dedicated explorations exist in making their configuration accessible to a non-technically-experienced audience. To facilitate a wider adoption of this approach to design and fabrication, we believe it also necessary to unlock the tools of this methodology to all designers, not just the digitally inclined.

This domain of research is not without contemporaries: similarly oriented robotics software frameworks, like the popular Robotic Operating System (ROS) Industrial (Quigley et al. 2009) and Robo.op (Bard et al. 2014), provide helpful resources for live-programming industrial robotics in tandem with computer vision techniques, potentially for architectural use, but fall short either in their accessibility to the general design community or the extensiveness of their scope of application. In contrast, select geometric modelling software add-ons compliant with ABB industrial robots—namely HAL Robotics, Onix (Elashry et al. 2014), and Lobster for Rhino 3D's Grasshopper plugin—leverage existing graphical algorithm editors to make code generation and IR simulation compatible with geometric information. Although these programs offer a more user-friendly and intuitive pipline for robotic programming, they do not integrate workflows for communication with cyber-physical devices. These software add-ons are not able to communicate directly and simultaneously with multiple forms of hardware, like industrial robots, sensors, and effectors, since they operate on different domain-specific languages. The gap between software and hardware becomes a hurdle for building a dynamic feedback loop in robotic fabrication. As a result, the rapid development by designers of online robotic fabrication processes integrated with feedback networks remains an intimidating, if not unfeasible, venture.

METHODS

Contemporary feedback networks in robotic fabrication often emphasize interactivity between cyber-physical elements and flexibility against indeterminate processes, promising a much higher level of integration between the physical processes of making and the virtual domain of information (Menges 2015). However, the emergence of cyber-physical systems in robotic fabrication imposes an intense challenge to the inexperienced or uninitiated. User interfaces for real-time control—like the Quipt gesture interface and Live (Batliner 2016) control platform—aid designers in creating fruitful human-robot interaction settings. But even once acclimated to or abstracted from the burdensome programming of industrial robotics, incorporating information feedback may require additional interconnected sensors, actuators, and processing software, potentially distributed across multiple platforms, each programmed in a different, domain-specific language.

Our objective was to simplify and consolidate the multiple platforms necessary to construct feedback networks for robotic fabrication into a central programming environment in order to minimize prerequisite knowledge while maintaining the full body of tasks otherwise handled by a more visibly complicated system. Our experiments prototyping feedback networks for use with robotics in design practice suggested that the application of this knowledge often follows a remarkably consistent profile. By exploiting the redundancies exposed by this profile, we developed a support toolkit of data structures and routines, providing simple, integrated software for the user-friendly programming of commonly-used roles and functionalities in dynamic robotic fabrication, promoting a methodology of feedback-oriented design processes.

Similar to the homeostatic processes for regulatory loops in biological systems, our prototype interfaces make explicit use of three interdependent software components, emphasizing the coordination of information exchange between sensory units—responsible for monitoring aspects of the fabrication environment—and a control center, which requests and processes these “stimuli” into physical actions executed by effector units, whose primary member is the industrial robot. Our intervention was to explicitly encapsulate these roles into designer-friendly customizable data structures housed in a single Python programming toolkit. Meanwhile, all inter-component communication and the domain-specific programming of hardware and our ABB IRB 4600 robotic arm are invisibly handled in the background within the toolkit, accessed intuitively from a collection of custom libraries (Figures 1 and 2).

By leveraging these common feedback roles into a designer-friendly programming interface, our ambition is that designers may more fully engage the orchestration, ordering, and design of dynamic information exchange among their environment, themselves, and their fabrication systems. The structures defined, protocols (a means for unrelated objects or systems to communicate with each other) created, and routines written were intended to be intuitive and to encourage the implementation of robotically achieved, materially driven fabrication, but generalizable enough to not restrict the users’ scope of development.

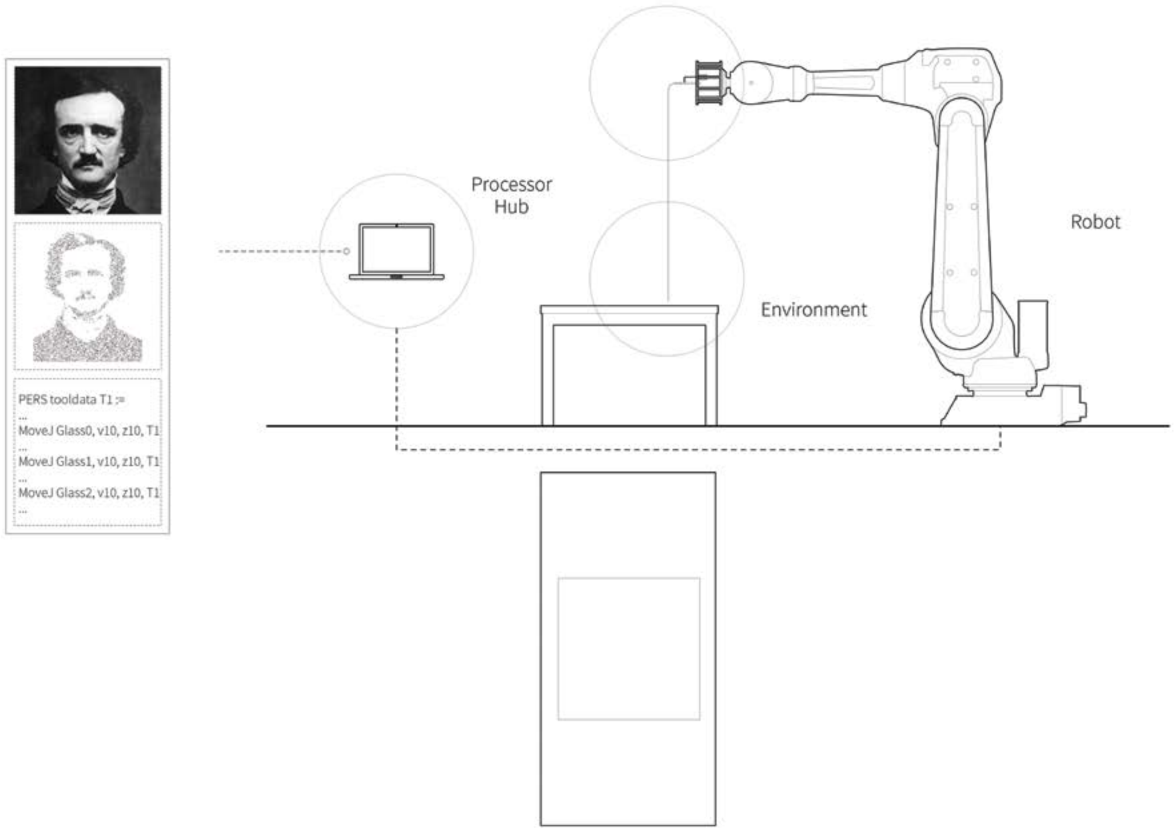
To realize this indeterminate exchange of sensory updates and instructions—necessary for dynamic feedback—our pipeline makes extensive use of the client-server communication model, implemented across all integrated cyber-physical components. In this model, clients and servers exchange messages in a request–response messaging pattern: to communicate, a relay of client requests and server responses are exchanged in a common language dictated by a predefined protocol, so that both parties know how to interpret their received messages. Accordingly, our toolkit employs a set of custom request-response messaging patterns and communication protocols appropriate for the interpretation and handling of the sensor-effector and robotic programming that would otherwise be conducted by users from scratch. In our pipeline, this occurs passively as a consequence of the user’s programming.

RESULTS

Prototype Feedback Scenario 1: Robotic Ink Drawing

In our first feedback-driven design scenario—a test in robotic ink drawing—particular attention was given to the dependency of the operation and programming of Effectors on finessing a stylized physical output through ink deposition (Figure 3). The grey scale information of various reference images was used to affect the location of target points for directing our industrial robotic arm’s motion: each pixel’s grey scale value was extracted and then sorted to find the image’s darkest points, generating initial centroids to attract 8,700 target points randomly populated within its bounds. These target points were clustered according to their closest centroid. For each cluster, a new centroid was calculated based on the mean of the points within it. By looping this process, target points were continually reorganized into clusters based on the grey scale value of the reference image, until none of the cluster assignments changed. The final set of points was then drawn by the industrial robotic arm (Figure 4).

In this drawing model, the style is considerably affected by the industrial robot’s speed, as well as the rate of ink flow from an effector—a customized drawing instrument—which consists of a brush and an automated ink feeder assembly. A valve attached to tubing that supplies ink to the brush controlled the flow rate of the ink. By manipulating the flow rate and the speed of the industrial robot’s motions, multiple dot styles were generated: with low industrial robot (IR) speed and high flow rate, ink was deposited in excess to the target point, creating an emissive effect, while a combination of high robotic arm speed and low flow rate contributed to dots of irregular shape. Alternatively, a dripping impression could be obtained by high IR speed and high flow rate, while low industrial robot speed and flow rate generated precise round dots. Here in particular, our developing toolkit facilitated the programming of specific robotic motions to



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3 Robotic Ink Drawing Loop.

4 Completed ink drawing of a portrait of Edgar Allan Poe, signed by Sulla, our ABB IRB 4600 industrial robotic arm.

operate in tandem with the above-mentioned drawing parameters produced by the effector, thus synchronizing drawing media, style of physical production, and image reference data into a single system. Moreover, programmed together in one consolidated file, we were able to engender more coordinated control of the industrial robot and the end effector in the precise management of ink deposition quality. This means of creating various drawing styles by manipulating IR speeds would later influence the generation and design of heterogeneity in material deposition (Scenario 3). Nevertheless, as an experiment in online robotic programming and effector coordination, our uni-directional flow of information had not yet demonstrated an integration of feedback within the design process.

Prototype Feedback Scenario 2: Robotic Wine Serving

In the subsequent model, our client-server structure was more fully utilized to build a reciprocal connection between cyber and physical spaces. Here, an indeterminate environmental factor—the location and presence of an arbitrary number of wine glasses—was incorporated into the execution process to guide the robot's actions in serving wine (Figures 5 and 6).

Our sensor, a ceiling-mounted RGB-D camera, was used to capture RGB color information paired with per-pixel depth information through requests to the object for updates. Using the resulting RGB color values, the boundaries of wine glasses were detected by comparing color properties with surrounding regions and grouping clusters of like-pixels into circular "blobs," allowing their centroids to be extracted as target points for the industrial robot. The corresponding depth values captured for these centroids allowed us to grab coordinates in three-dimensional space for the glasses, which were transformed according to the coordinate system native to the industrial robot. Finally, a parameterized toolpath for the IR was generated by connecting these target points in a minimal route. This begins with the robot's rest position while "on break" and then is altered live at the incident of a guest's adjustment of the position of a wine glass. The entire process was enclosed within a continuous loop instigated by the absence or presence of wine glasses on a serving table and on call throughout a welcoming reception for the college (Figures 7 and 8).

In this project, we underscore the interdependence of sensory updates with online robotic programming to accommodate an unpredictable environment. Execution loops for wine pouring were parameterized around an indeterminate, perhaps empty or even unstably positioned, list of glass locations in 3D space. Finesse and refinement of the extrusion loop was important in order to avoid spilling or harming guests. Yet, in a problem space of such volatility, the live adjustment of complex behavioral processes could be programmed concisely and entirely in the Python programming language as an intuitive description of data transformation, commands, and execution loops. We believe this flow of information from an erratic human environment, through a digital environment for processing, and then reactively fed back to the physical realm is emblematic of a new paradigm for fabrication.

Prototyping Feedback Scenario 3: Dynamically Adjusted Extrusion

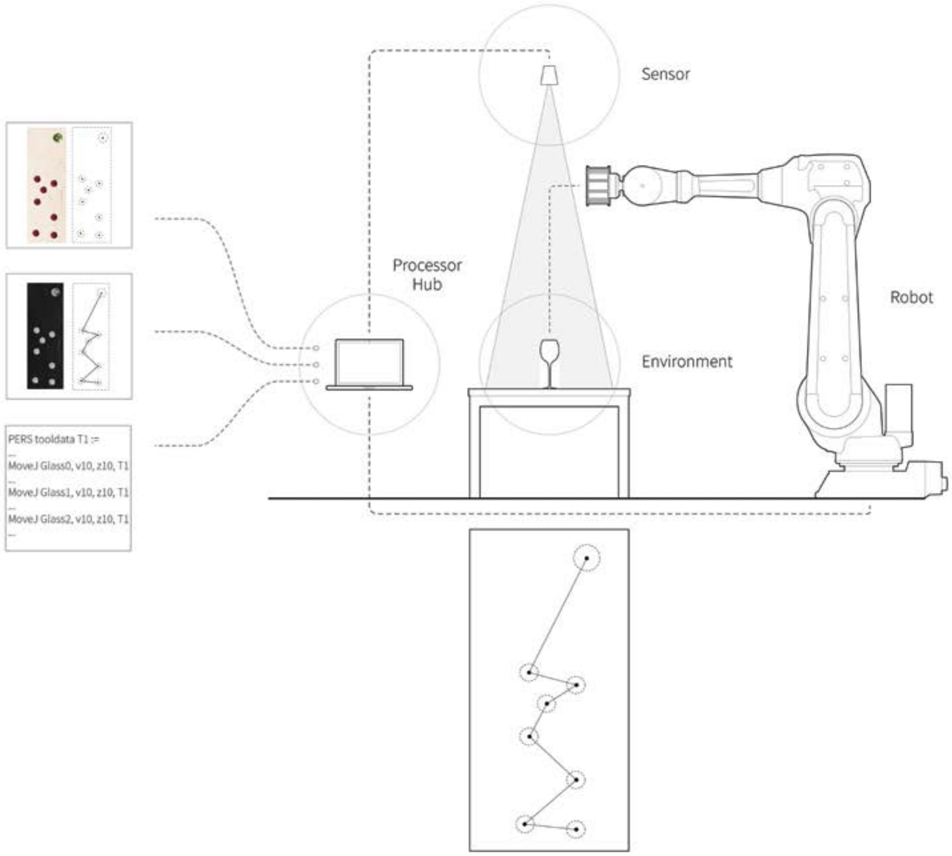
An ongoing third case study synthesizes the approaches explored in the robotic wine serving and ink drawing investigations with a stronger relationship to the feedback-based manufacturing of non-standard physical elements. The ink drawing behavior previously described is translated to a robot-mounted extrusion system, whose heat and deposition speed are dynamically adjusted by the user while material is deposited. The interaction protocol for adjustment relies on a block-based interface which situates the user and interaction system behind a glass wall, proximal but safely distant from the robotic arm's operation (Figure 9). Deposition properties, as well as stopping commands, are mapped to colored sides of the block, read by a camera, while a continuous extrusion profile is parameterized by the position of the block relative to an infrared distance sensor (Figure 10). Practice-oriented, our developing work sees the production of custom-modified components as a real-time engagement between fabrication tool and user, pairing an indeterminate updating of commands with the potential embedding of qualitative assessment into the process of design making.

DISCUSSION

With the rise in emphasis of pseudo-cognitive, reactive machines, a convergence between design and making is surely forthcoming—cyber-physical systems, even purely linguistically, predicate a marriage of digital and physical realms. This holds great promise to not just make possible, but make seamless the co-evolution of material and digital complexity in the built environment. Positioning and maintaining the design fields at the forefront of this trend in innovation must involve an update to the methodologies of our tools, which describe and reveal the intertwined processes for design and making, mostly through code. Critical to staying engaged in this shift is the design and generation of tools that incorporate complex behavioral programming in a user friendly and approachable tooling environment. Our intent was to develop a kit of programs and software interfaces to facilitate this shift, both in our lab and across disciplines whose research might benefit from its adoption.

Consequently, the described development of this toolkit was undertaken as a series of recognizably playful scenarios, both to eliminate the non-essential hurdles often encountered in more practice-oriented investigations, but also because their principles could be extrapolated into architecturally applied digital fabrication techniques. For example, we may re-assess the live adjustment of ink deposition—dripping or brushing properties, flow rate, deposition speed—as a direct antecedent for dynamic fine-tuning in additive manufacturing processes. The real-time modification of extrusion properties—viscosity, extrusion profile, or deposition speed—is a close reality, either as a corrective measure for otherwise "bad prints" or perhaps on the basis of qualitative assessments, decided by the designer in media res. Similarly, the interaction between humans and robots engaging in cooperative activity, as in our wine serving scenario, anticipates those feedback-based fabrication environments where robotic adaptation to indeterminacy is preeminent. This is especially true in person-shared fabrication settings where human engagement implies both a concern for safety and a promise to include receptivity in digital handcraft.

Importantly, any rigorous application, including both those undertaken and those suggested, usually requires several iterations of prototyping with equivalent rigor: ours involved the continual formulation, construction, assessment, and re-formulation of behavioral processes and information exchange. Programming



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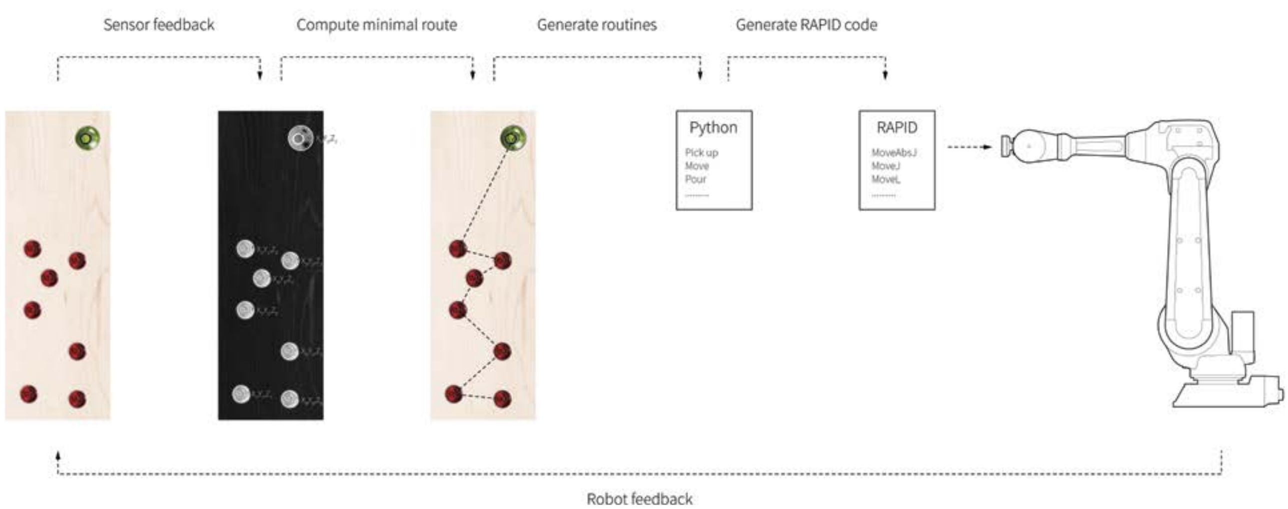

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5 Robotic Wine Serving Loop.

6 Robotic Wine Serving Workflow Diagram.

7 Dynamic wine pouring with object detection, shortest path calculation between objects and immediate tool path generation for pouring. This test highlights two levels of feedback: 1. Through a user moving their glass in space and 2. Between multiple glasses in shifting locations on a table. The tool path adjusts accordingly in real time for both cases.

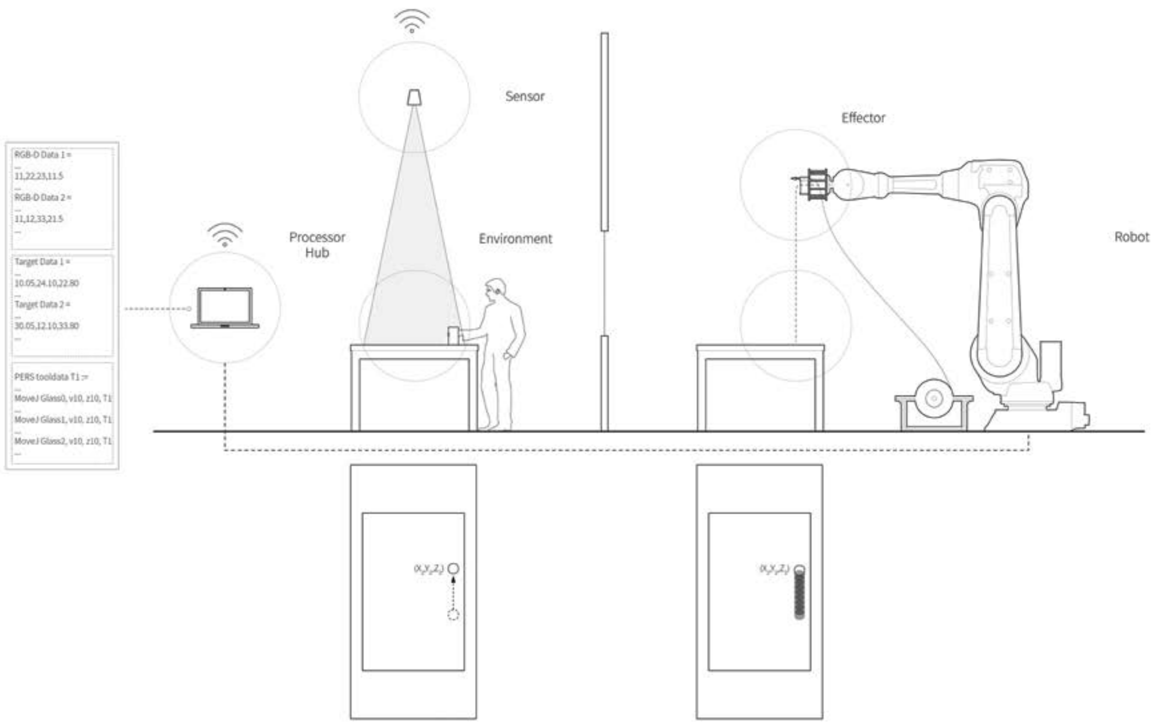
8 Dynamic tracking of glass object in an unpredictable environment for accurate pouring.

and testing models for environmental feedback constituted the design process. Access to our software toolkit with a predilection for feedback-driven design allowed the process to proceed with efficient use of time and energy.

As acknowledged, the ambition of our toolkit is primarily software-oriented. In opening industrial robotics to the design fields, our foremost aim is to alleviate the difficulty in programming feedback into cyber-physical systems, and thereby also improve the convenience of building their hardware accompaniments. Nevertheless, to accommodate lapses in electronics-building experience, we recommend using existing modular, ready-to-use tool sets for the Arduino platform, which simplify and condense the learning process significantly. One popular tool set, Grove, takes a building block approach to assembling electronics, providing plug-and-play modules for rapid physical assembly, which intuitively integrates with the programming of Sensor and Effector objects through our toolkit.

CONCLUSION

This work aims to develop a toolkit including software, custom digital design tools, and hardware for robotic fabrication and intuitive user interaction. While nonlinear concepts are widely applied in analysis and generative design in architecture, they have not yet convincingly translated into the material realm of fabrication and construction. In this paper, we demonstrate three case study projects that probe cyber-physical interactions in the context of robotic fabrication. This allows for the generation of dynamic and immediate tool path responses in shifting environments. These projects present useful scenarios that have immediate translation into a materially directed generative design process in the context of robotic fabrication and assembly. The main thrust of this work concerns the evolution of material and digital complexity in the built environment through prototypical design experiments that rigorously abstract, extend, and translate dynamic behaviors and models with the end goal of generating adaptive architecture and material assemblies that operate at the



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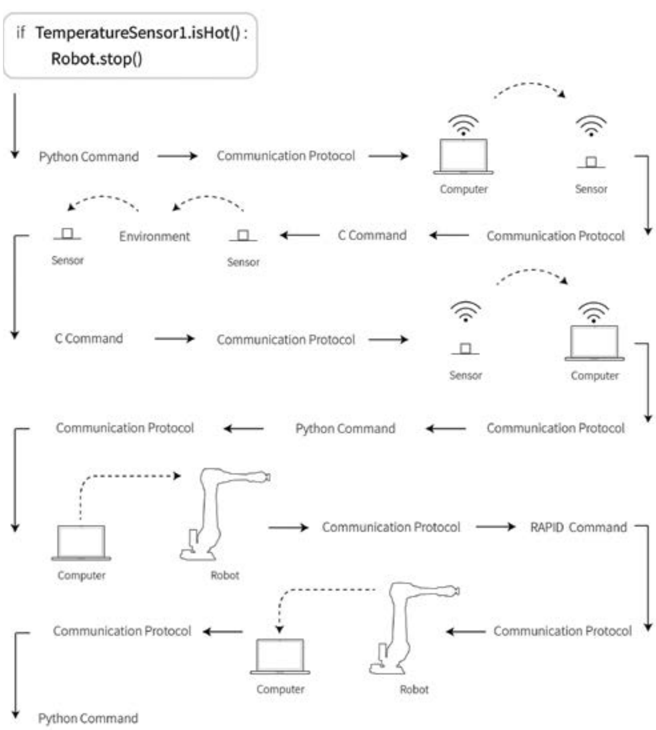

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9 Dynamically Adjusted Extrusion Loop.

10 Diagram Of the Complete Execution Flow.

human scale. Our design process moves fluidly between analog and advanced digital procedures, often inserting the human hand or digital handcraft in the meaningful and rigorous negotiation of scale and complex behavior. As the gap between digital design model, shop drawing, and fabricated result continues to diminish, we seek to learn from fabrication models and natural systems that do not separate code, geometry, pattern, material compliance, communication, and form, but rather operate within dynamic loops of feedback, reciprocity, and generative fabrication. This paper presents one approach to the negotiation of this gap through methods, tools, hardware, and software that are now being implemented in 6-axis robotic additive manufacturing as well as dynamic object detection, placement, and assembly.

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IMAGE CREDITS

All Figures: Moorman, Liu, Sabin, 2016

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