SEEING IS DOING:
SYNTHETIC TOOLS FOR ROBOTICALLY AUGMENTED FABRICATION IN HIGH-SKILL DOMAINS

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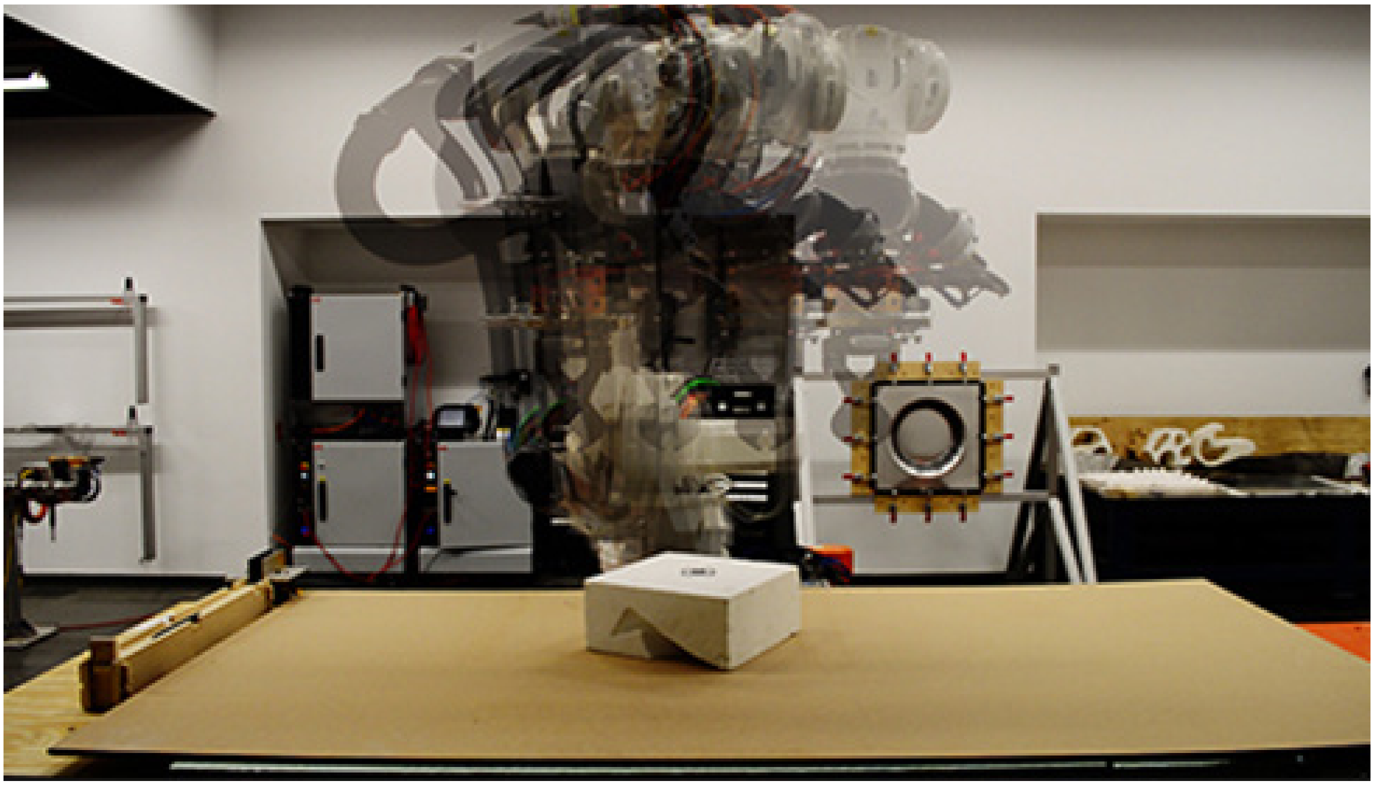


1 Robot Searches for Stock Definition (Jeffers 2014)

ABSTRACT

This paper outlines the development of an open-source, robotic toolkit that enables the integration of real-time sensing for design and fabrication in high-skill domains. This constellation of tools serves to augment standard CAD/CAM workflows where tool path creation and tool path execution are divided into two distinct operations. This sequential split between the virtual design, control and visualization of geometry for fabrication—seeing—and the computerized control of machines interacting with physical material—doing—detaches bodily skill from standard building techniques and furthers the tendency for digital technologies to curtail haptic feedback in the architectural design process. Despite an early inheritance from industrial manufacturing in architectural robotics (dictated by the rubrics of efficiency and safety), promising paradigms for human-machine collaboration in high-skill domains are rapidly emerging in many fields, and are poised to question the separation of seeing and doing ingrained in commonly held ideas of architectural design process and authorship.

CONTEXT/MOTIVATION

The human body fosters a wealth of tacit knowledge vital to cultural, political and economic dimensions of human life. Think of the learned dexterity of a surgeon's fingers, the buoyancy of a dancer poised to leap, or the sureness of experienced hands guiding a chisel through natural wood. Despite the body's centrality to many important modes of human endeavor, technology has often displaced bodily skill with mechanized production. In the architectural arena, industrial manufacturing of architectural building components has significantly altered the relationship of human craft to the design and production of the built environment. The skill of the craftsperson's hand has been all but erased, replaced instead with repetitive and unskilled labor.

Despite the prolonged history of industrial production in relation to human skill, this need not remain the case. Robotic fabrication and rapid prototyping are disturbing the equilibrium of the design and industrial manufacturing of architectural building components (Sharples, Holden and Pasquarelli 2002). These emerging technologies enable small-scale production, afford a higher degree of customization and allow designers greater access to the means of building production. The difficult relationship between the human body and industrial machines needs to be reformulated in this new context. Ultimately, a collaborative relationship can emerge where the salient characteristics of human skill and machine precision work in tandem toward augmented paradigms of fabrication. One significant hindrance to the incorporation of emerging collaborative technologies in architectural design and production is the fact that the historical definition of architectural authorship hinges on the autonomy and import of architectural representation—seeing—as distinct from building construction—doing.

HISTORICAL PERSPECTIVES

Mario Carpo, in The Alphabet and the Algorithm, constructs a historical context for understanding the architectural design process relative to the discipline's need for authorial control over building construction. Carpo deploys two categories borrowed from philosopher Nelson Goodman, to underpin our understanding of design agency—the autographic vs. the allographic. These two paradigms are epitomized in the legacies of Alberti, the primogenitor of architectural drawing, and Brunelleschi, the often cited embodiment of the master-builder. According to Carpo, the architectural drawing is the locus of "fully authorial, allographic, notational status"(Carpo 2011). To the extent that drawing legitimizes the architect as sole author, it also necessitates removing the architect from the tangible domain of building.

Robin Evans, a strong proponent of the generative potential of architectural drawing, starkly exposes the implication of this logic:

> These two options, one emphasizing the corporeal properties of things made, the other concentrating on the disembodied properties in the drawing, are diametrically opposed: in the one corner, involvement, substantially, tangibility, presence, immediacy, direct action; in the other, disengagement, obliqueness, abstraction, mediation and action at a distance. (Evans 1997)

In Evans' estimation, there are a number of potential responses to this diagnosis, but they all stem from the salient reality that the differences between seeing—visualizing through an abstract medium—and doing—working directly with material—are irreconcilable. Ultimately, this rubric reduces to the logic of either/or, leaving the designer to shift relative emphasis between these two divorced modes of creative process.

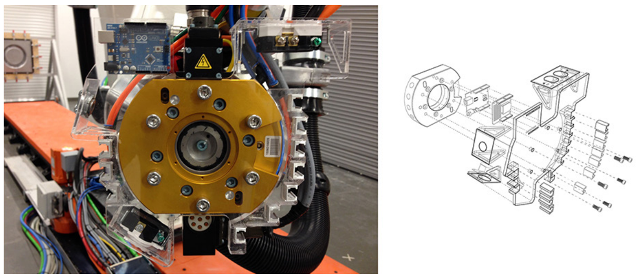
CONTEMPORARY TRENDS

Contemporary modes of practice and emerging technologies have dislodged the drawing from its privileged position at the heart of the architectural design process and begun to suggest that the binary opposition between seeing and doing is dissolving. Discussing recent developments in design software, Carpo argues that digital workflows "will increasingly merge and overlap in a single, seamless process of creation and production... One can discuss, design and make at the same time—just as premodern artisans and pre-albertian master builders once did." (Carpo 2011) Despite this promise, many CAD/CAM workflows still underscore the fundamental divide between virtual representation of geometry and physical manipulation of the material world. Even though the medium has changed from analog to digital, instructions are still produced through representational means, then executed in the physical environment. Changes at the point of physical production often result in an arduous editing and re-exporting process.

By comparing recent developments in robotic technologies to earlier architectural implementations of industrial robotics, Martin Bechthold finds promise in rethinking standard CAD/CAM workflow:

> Both approaches rely on a unidirectional information flow from design model to code generator and ultimately to the robotic manipulator. A radically different approach to addressing the complexity of design and robotic fabrication systems is bottom-up strategies that rely on local processing and control. Early studies show promising robustness and adaptability, albeit yet unproved in the fabrication context. (Bechthold 2010)

2 Example of Image Guided Surgery with Motion Tracking Surgical Tools and Information-Rich Visualization (Descoteaux 2014)



3 Prototype of Sensing Tool Plate Mounted on Robot (Jacobson-Weaver, Contral 2014)

Coupling sensing applications with robotic technologies entails rethinking the directionality of this standard workflow and encourages hybrid modes of digital practice where simultaneous visualization and material manipulation inform the design process.

CASE STUDIES

There have been many recent developments of hybrid work environments in high-skill domains, which integrate seeing and doing through digital workflows. One instructive example, from the field of medicine, is *Image Guided Surgery* (*IGS*). IGS is used to augment delicate procedures to encourage minimally invasive surgical techniques. IGS uses surgical tools that are mapped in real-time within high resolution, information-rich visualization using diffusion MRI (Figure 2). IGS uses motion tracking cameras to locate infrared fiducial markers placed on the operating table, various surgical equipment, and the patient's body. This allows a surgeon to track handheld tools in real-time and see the position of these tools within the context of advanced medical imaging of a patient's brain or spine. IGS bridges the divide between the physical environment of the operating theater and the virtual space of the digital image. The contextually aware tools in this system augment the manual dexterity of the surgeon, and allow for smaller incisions and greater precision during surgery. What might Robin Evans think today of a process that is both abstract and tangible, simultaneously virtual and real?

SENSING TOOLKIT FOR ADAPTIVE FABRICATION

Adaptive fabrication is a responsive construction approach that allows a task to update based on data received from external sensors and events. These techniques require the implementation of external sensors and hardware, communications control from raw sensor output to controlled robot motion and signal/power translation from a robot's dress pack to external devices and custom end-of-arm tools. The following section describes the development of three open-source toolsets for adaptive robotic fabrication. These toolsets combine techniques in proximity sensing, computer vision (CV), low-fidelity force feedback, and motion capture (MOCAP) to augment standard industrial robot configurations with real-time control. Each custom tool encodes a contextual awareness of the immediate physical environment within the robot's work cell and suggests a range of potential applications for developing human-machine collaboration in high-skill domains. When these tools are layered together, they demonstrate how live control of an industrial robot can be safely driven by environmental stimuli, to augment standard off-line programming and call into question the historical distinction between seeing and doing in architectural design.

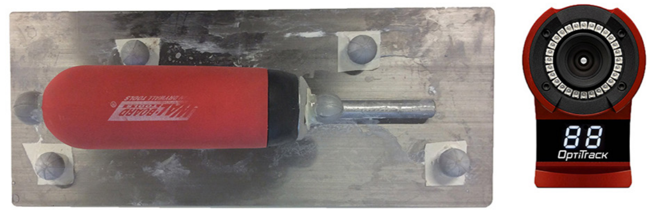
During the development of these three toolsets, the research team realized a need for a standardized approach to how sensing modules are integrated into adaptive fabrication workflows. We have, therefore, begun developing a hardware component that standardizes integration for a number of the most common smart tool peripherals: cameras, projectors, sensors and microcontrollers. Inspired by open source platforms, like Arduino and Processing, this "adaptor plate for smart tools" facilitates plug-and-play development for custom end-effectors. It brings end-of-arm high- and low-voltage power supply, has wireless and wired communication for off-line programming and integrates an arduino for extensible physical computing using sensors, motors and actuators (Figure 3).

HAND-CRAFT SKILL TRANSFER IN ROBOTIC FABRICATION

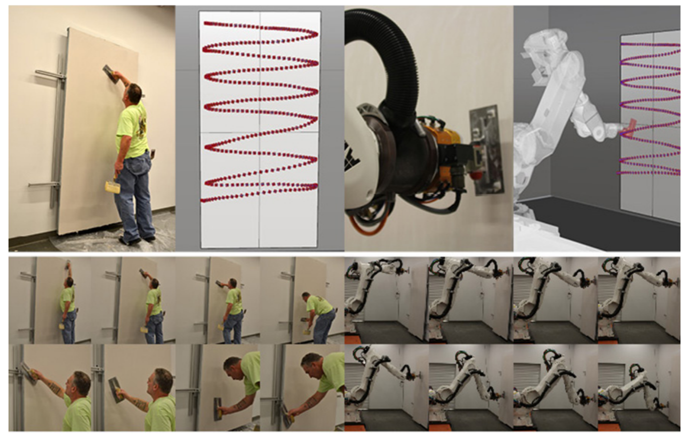
In many of the traditional building trades, there is a profound repository of learned skill and embodied know-how. This bodily knowledge can be leveraged in robotic fabrication scenarios using real-time sensing and adaptive motion planning techniques. Rather than applying top-down, offline motion programming generated in the abstract modeling environment of a computer screen, we are exploring how human skills can be transferred directly to generate informed robotic motion control. This workflow moves designers and craftspeople away from offline programming to gestures and sensor-embedded smart tools to interact with robot collaborators in highly skilled building applications. As an initial case study, we have been collaborating with a local chapter of the Operative Plasterers and Cement Masons International Association (OPCMIA) to test this workflow in the high-skill domain of applied architectural plaster. Architectural plaster provides a compelling case study in skill transfer because of its rich history of handcraft and the learned dexterity needed to shape soft building materials with precision.

Our team is currently using Motion Capture technology (MOCAP) to track the hand tools and learned motions of experienced plasterers. We have installed a six camera array in a robotic work cell, distributed to track basic plastering techniques such as rendering a flat wall section with smooth plaster. Infrared reflectors are placed in asymmetric patterns on plastering trowels (Figure 4) and tracked in real-time. Using commercially available MOCAP systems, we can track hand tools at a sampling rate of 120 fps with submillimeter position and 6DOF orientation at each frame. Skill abstraction from raw motion-tracking data is used to directly inform robot motion control of a plastering trowel. In order for the workflow between human gesture and robotic motion in construction settings to be fully functional, robust algorithms are needed to parse live streams of raw tracking data to recognize, smooth and locate tool paths in physical space. Further, the interplay between live tracking and robot response can be visualized by plotting tracking targets, instantiating tracked tools in virtual models of the construction environment and simulating robot motion generated from human gesture (Figure 5). A series of custom Grasshopper components were developed to enable fluid visualization and refinement of this workflow.

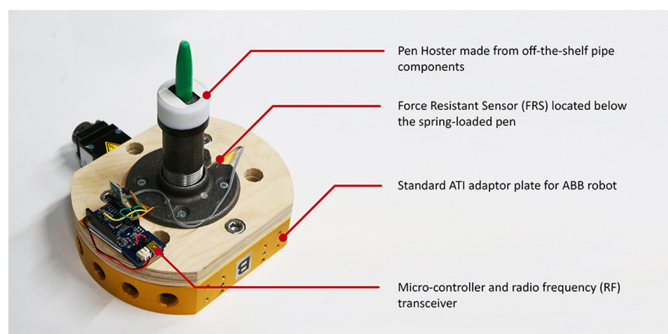
In addition to safe translation of raw tracking output, future development of this workflow will entail bridging the disparate worlds of constraint-based motion planning (which excels at open-ended, indeterminate tasks and real-time decision making) and CAD-generated offline programming (known for robust geometric construction and visual feedback during the design process).



4 Plastering Trowel with Infrared Reflectors for Tracking (Bard 2014)



5 Skill Transfer from Trained Plasterer to MOCAP Tracking to Robotic Motion (Bard 2014)

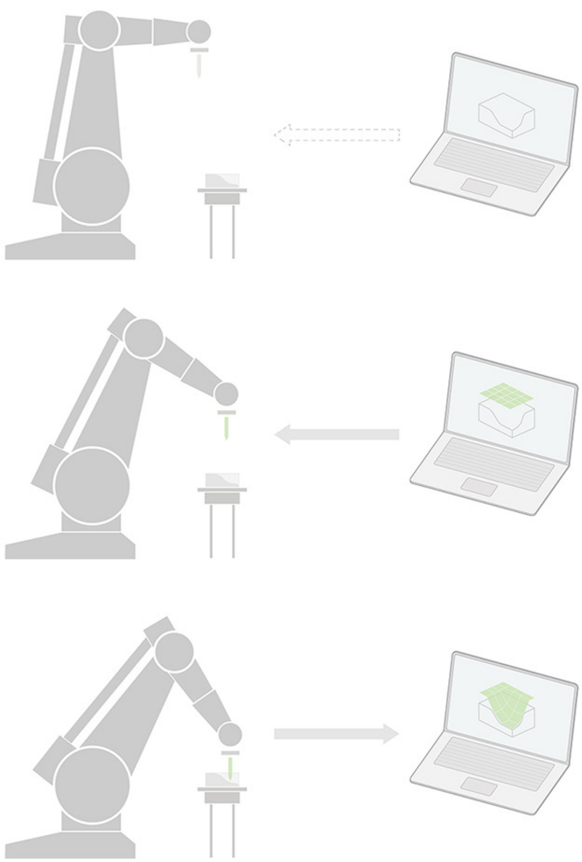


6 Pen Tool with Low Fidelity Force Feedback, Prototype (Gannon 2014)

DIGITAL-PHYSICAL SYNCHRONIZATION IN ADAPTIVE FABRICATION

With conventional methods in robotic fabrication, path planning, motion control, and tooling operations are primarily derived from geometry generated in CAD software. The digital geometry in a CAD file, however, is only an idealized representation of the actual material or canvas in physical space. It often takes many iterations of a designer editing files, exporting, then physically testing with the robot before the virtual context modeled in CAD precisely aligns with the physical environment. This division becomes even more exaggerated during adaptive fabrication workflows: it is incredibly difficult to effectively manage static CAD files when the robot, material and physical environment can all dynamically update based on data received from external sensors and events.

To create more fluid digital-physical workflows for adaptive fabrication, we developed a pipeline for synchronizing digital geometry with its physical counterpart. This pipeline feeds information from a sensor-embedded smart tool, through the robot, and into a CAD file. In our initial case study, we created a smart pen with a



7 Once a rough approximation of a physical form is digitally modeled (top), the pipeline sends a point coordinate for the robot to move (middle). When touching, the smart pen sends analog sensor readings to through the pipeline over radio frequency (RF). A command is triggered to record and sent the robot's current world position the CAD file over Open Sound Control (OSC) (bottom) (Gannon 2014).

contextual awareness of when and how hard it is touching something. This custom end-effector integrates a pressure sensor, microcontroller, and a pen to give a low-fidelity sense of touch to the robot (Figure 6). This sense of touch can be used to update a CAD file by correlating sensor readings to the robot's position data.

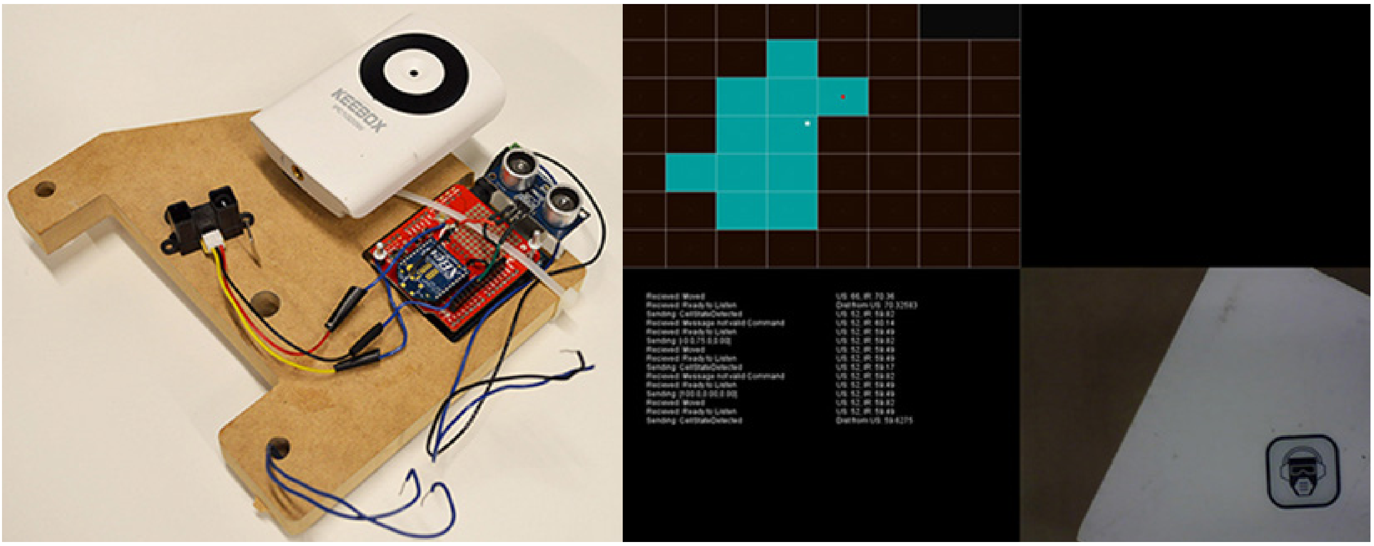
As a proof of concept, we created an example application that uses the smart pen on the robot to 3D scan an existing physical form and regenerate its digital counterpart. First, we create a rough 3D model of the form using a standard CAD program (Figure 7a). A grid of points is then generated and sent to the robot as move commands; the more points the higher resolution the scan. The robot uses each point as a starting position, and iteratively lowers until the smart pen indicates that it is touching a surface (Figure 7b). Once touching, the sensor data from the smart pen triggers the robot to send its current position to the CAD file. This real world position then replaces the digital starting point, and over time, the physical surface gets translated into the digital file (Figure 7c).

While this proof of concept is relatively simple, there are larger implications for synchronous digital-physical workflows. One potential application is mapping different zones of materials in heterogeneous assemblies. For example, changing the sensing capabilities of the smart tool from a pressure sensor to a hall effect sensor would enable the detection metal screws in wood. Once detected, the position of each screw could be sent back and mapped within a CAD file, and consequential tool paths could be regenerated to avoid contact with the screws. Similarly, a photosensor would enable the detection and mapping of reflective versus non-reflective materials, such as glass or resin and wood. Regardless of sensing or assembly, using smart tools to directly link the accuracy of the robot to a CAD file enables designers to build more dynamic and integrated relationships between geometry and robotic operation in adaptive fabrication scenarios and begins to underscore the potential of seeing and doing in hybrid fabrication environments.

CV AND PROXIMITY SENSING FOR REAL-WORLD OBJECT DETECTION

Stockfinder is a vision-based workflow for locating and manipulating arbitrarily placed objects in a given work environment. In a typical-use scenario, the process begins with robot alignment and centering: the user jogs the robot's sensory-tool to face the desired object. A larger scale rough-search is then conducted, using a low-res IP-camera and CV image association algorithms to locate the object in the camera view (Figure 8). The user selects the sub-image that bounds the view of the object in the initial pose. After the selection, each frame performs a targeted association, calculating the pixel distance and direction to the best-match pixel-pairings, statistically culling outliers to avoid moving to a near-match. The robot will then incrementally align the camera center with the rough center of the selected object as it is detected. Upon alignment, depth value is detected by pulling multiple pings from a depth-sensor. Motion along the normal proceeds to a defined calibration height, giving a safe distance of approach.

The next stage constructs a depth image with calibrated search criteria. Rather than parsing meaning from a surplus of data generated with a commercial depth camera, this approach builds definition from the bottom up. The process begins by moving the robot to the first cell center and detecting depth. This process continues to populate an entire search grid. Once the initial depth values are sensed in the grid, the search-space is reduced, as refining the entire grid at each level would increase search time by an enormous factor. The search process ignores all cells that are not "edges" of a stock-object. Knowing the current target height, calibrated from the second stage, we know when



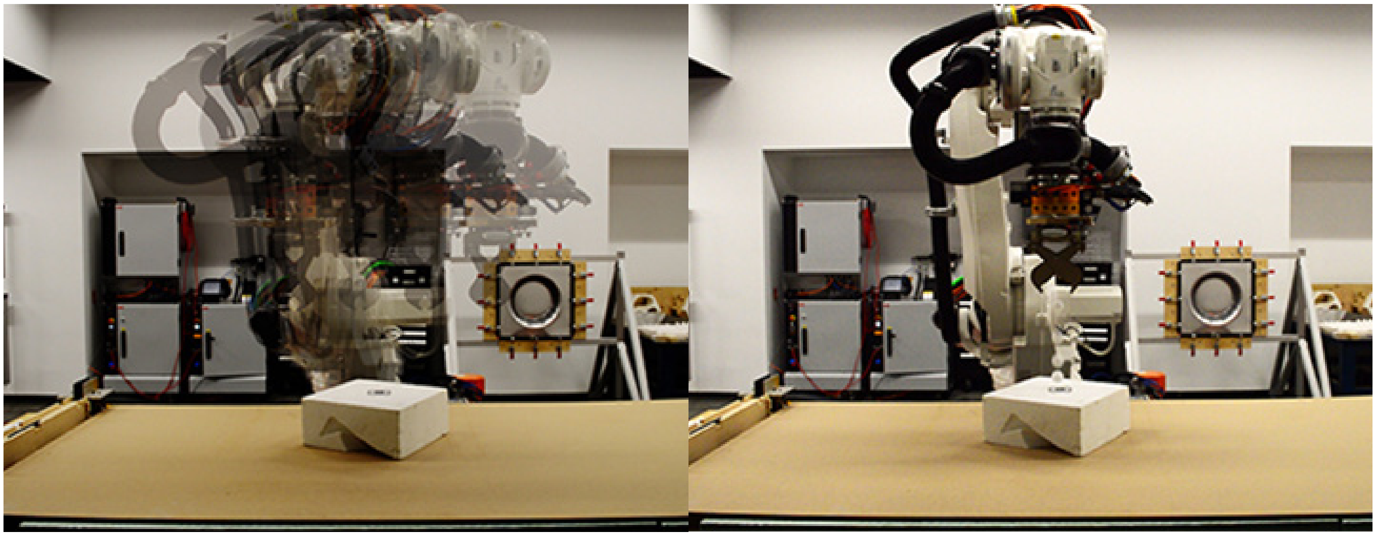
8 (left) Tool Prototype with Camera and Depth Sensor. (right) Grid Cell Search for Stock Definition and Refined Center (Jeffers 2014)

a grid cell is within tolerance of the original height, or registers some other depth. We can now define edges as cells that neighbor a difference in this state, and ignore cells that have the same state as all of its neighbors. These cells are then subdivided and the search recurses until some desired level of fidelity. We can associate the level of cell subdivision to robot-space and therefore real-space dimension, so we know exactly with what tolerance we are defining the resultant digital representation of the target object. From this point, we now have a more refined center, as well as an approximate of any two-dimensional shape that is the user's Stock Object. More importantly, we have these stored as robot-relative coordinate information, the critical component in successfully operating on a known object in the robot's workcell (Figure 9).

OUTLOOK

While there is heavy technical overhead for learning and using industrial robots, the promise that robots are designed to have extreme flexibility in their installation and use overshadows other dedicated CNC machines with rigid limitations to their functionality. The open-ended tooling of industrial robots complicates processes for integrating path planning, tooling operations, electronics and software into robotic programming. As a result, a large amount of time, energy and resources are invested in reinventing—rather than innovating—how we use industrial robots in architecture. With increasingly more architectural institutions incorporating industrial robotics into their pedagogy and practice, we believe that developing and encouraging shared tools will help architectural robotics advance further, faster.

Our intention is to open-source a stable version of a sensing adapter plate. However there are larger, systemic challenges that will impede the adoption of a standardized development platform for architectural robotics. The greatest challenge comes from the robot itself. Each "brand" of robot uses its own set of proprietary hardware and software; so what may work for an ABB robot may not run on a KUKA or Staübli. Moreover, the more commonly used software tools for communicating with industrial robots (Rhino, Maya, Grasshopper, HAL, etc.) are also proprietary, and susceptible to rapidly shifting trends in technology. Despite these challenges, we still see immediate value in the ability for students and researchers to have a standard for integrating custom end-effectors with vision and sensing systems, not only to greatly reduce setup time, but also to foster a community of sharing in architectural robotics.



9 (left) Robot Searches for Stock Definition. (right) Robot Drops Object at Refined Stock Center Point (Jeffers 2014)

CONCLUSION

Although this paper highlights a small constellation of sensor based tools for adaptive robotic fabrication, the authors recognize that robust human-robot collaboration in high-skill domains requires further development in many key arenas. These include:

1) Questioning the context for visualization in design practice. Digital media is often constrained to the physical local of individual computer screens in the design process. In hybrid workflows relevant, information-rich visualizations need to be spatialized within the fabrication environment—whether that means projecting ambient media or delivering localized visual feedback where tool meets material, the location and orientation of digital media can inform physical making.

2) Developing real-time communication between physical sensors, generative models and robotic manipulators. Making need not be the rigid execution of some predetermined intent. In the traditional crafts making was a continuous unfolding of the creative interaction among a designer's intent, the particularities of material behavior and ongoing adjustments to physical tools. In a digital context, this unfolding also involves the interaction of physical sensing with generative computer models.

3) Skill development in hybrid physical/digital workflows. Currently many of the most highly skilled building trades are dying out. Many of the most highly skilled hands have little digital literacy and most of the digitally literate lack the dexterity gained from sustained interaction with physical material. In the near future there will be an increasing number of digital/physical workflows that will reward practice.

Despite historical definitions of architectural authorship bound to the distinction between seeing and doing ,and the discipline's inheritance from industrial manufacturing, new robotic and sensing technologies are forcing us to reconsider the relationship of human skill to mechanized production. Ultimately, digital design practice is pointing us toward hybrid workflows where rich visualization and physical material manipulation inform the design process simultaneously. This paper suggests basic workflows and toolsets to begin exploring this hybrid design context, but the full potential of seeing while doing in the architectural design process remains uncharted.

REFERENCES

Evans, Robin. 1997. *Translations from Drawing to Building and Other Essays*. MIT Press.

Sharples, Holden, and Pasquarelli. 2002. *Versioning: Evolutionary Techniques in Architecture Design*. Wiley.

Carpo, Mario. 2011. *The Alphabet and the Algorithm*. MIT Press.

Bechthold, Martin. 2010. "The Return of the Future: A Second Go At Robotic Construction." *Architectural Design* 80(4).

IMAGE CREDITS

Figure 1. Jeffers, Michael (2014). Stockfinder. Carnegie Mellon University.

Figure 2. Descoteaux, Maxime (2014). Image Guided Surgery. Sherbrooke Connectivity Imaging Lab. http://scil.dinf.usherbrooke.ca/.

Figure 3. Jacobson-Weaver, Zach (2014). Modular Sensing Toolplate. Carnegie Mellon University.

Figure 4. Bard, Joshua (2014). Robotic Plastering. Carnegie Mellon Univerisity.

Figure 5. Bard, Joshua (2014). Robotic Plastering. Carnegie Mellon University.

Figure 6. Gannon, Madeline (2014). Pen Tool. Carnegie Mellon University.

Figure 7. Gannon, Madeline (2014). Pen tool. Carnegie Mellon University.

Figure 8. Jeffers, Michael (2014). Stockfinder. Carnegie Mellon University.

Figure 9. Jeffers, Michael (2014). Stockfinder. Carnegie Mellon University.

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