SIMULATIONS AND SAND CASTLES

AN EXPLORATION OF INDUSTRIAL ROBOTICS IN ARCHITECTURAL DESIGN

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This paper represents my own work in accordance with University regulations.

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INTRODUCTION

This is not a thesis on robot overlords. It is a thesis on the clever uses of remarkably dumb yet powerful instruments. Industrial robots are not a new invention, but architects have only recently adopted the six-axis robotic arm as a tool for making. But how can architecture benefit most from the industrial robot? Thus far, robots are used primarily by architects for custom fabrication, but these processes are unidirectional and do not realize the full potential of the robotic arm. The architecture firm Gramazio & Kohler laud the industrial robot as a generic tool,[1] and it is generic because it is precise and dumb; the robotic arm can accurately and repeatably move to specific points in space with a specific orientation, but does not have any awareness of space or material around it. Anything more than moving to programmed points in space requires additional computers, sensors, and human inventiveness. Its motion is intuitive, as it mimics the movement of a human arm and can have incredible strength, but should not be confused with autonomous robots that have 'intelligence'.

Industrial robots have been used in automotive factories since 1960, and the first anthropomorphic robot 'arm' driven by electromechanical motors reached the market in 1973 and 1974.[2] During this time, architects took little notice. Some that were interested in the intersection of computer intelligence and architecture at the time, such as John Frazer and Nicholas Negroponte, were primarily focused on creating custom electronic systems.

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[1] Gramazio & Kohler, Digital Materiality in Architecture, 9

[2] History of Industrial Robots: from the first installation until today, International Federation of Robotics

‘Smart’ architecture and embedded electronics still remain a point of interest today, however, market robotic arms provide architects with a diverse tool that enables novel processes of translation between the digital and physical worlds. Built to complete repetitive tasks on the assembly-line, such as welding, caulking, or moving, the six-axis robot first entered the field of architecture as a re-purposed manufacturing tool; architects and engineers developed repetitive brick stacking and milling procedures to create architectural objects from digital designs. The robots provide architects with an unprecedented degree of spatial precision, but architectural appropriation is destined to diverge from manufacturing-like projects.

What purpose should industrial robotics serve in the field of architecture? The construction of building elements and production of architectural representation continues to be explored, but how robots can contribute to an architectural space through augmented design processes or as embedded architectural objects requires further development. The robotic object, as we shall see, often eclipses the conceptual narrative of a project, and becomes the narrative itself. There seems to be a fascination with the industrial robot that yields projects *for* the robot as opposed to projects *with* the robot. These projects often include a well-produced video clip with exaggerated six-axis movements. Such a fascination can perhaps be employed generatively, as opposed to being a mere distraction. The coordinated movement of the axes is interpretative and mesmerizing, and captures imaginations in the same way that Transformers slide in and out of different configurations.

‘Robot’ is of course a loaded term within pop culture, and originates from the Czech word *robota*, meaning ‘forced labor’.[3] The pop culture depiction of robots is often of a clunky humanoid robot like C-3PO from Star Wars, or Robby from Forbidden Planet who serve their respective human masters. ‘Robots’ are not often perceived as graceful, and even dancing ‘the robot’ evokes jerky, discontinuous motions. The industrial robot, however, can move gracefully in the same way that a dancer would express themselves with his or her arms. Their precise, performative movements open up exciting opportunities for real-time architectural simulations and continuous design feedback. Robots can enable mobility and adaptation in architectural design.

In the 1960s, architects and researchers such as Cedric Price and the Architecture Machine Group were interested in how technology could manifest itself in an ephemeral architectural form that physically moved into new arrangements. Price argued for a ‘calculated uncertainty’ in architecture, in which a building could digest user feedback to adapt rapidly to changing social and cultural contexts. His Fun Palace, for example, was designed for rooms to mechanically reorganize to accommodate the necessary program. Such adaptive parameters, which were central to the discussion of technology and architecture at the time of Price, are secondary to the technological processes in the discourse of digital fabrication with robotics today. Yet in the current digital age, how architecture can be ‘smart’ and adaptive to

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[3] Intagliata, Science Diction.

user needs still deserves attention. As can be seen in the 2008 Venice Biennale project by Gramazio & Kohler, among many others, novel fabrication and construction processes are at the forefront of the discourse in digital instrumentation; however, the performability and precision of robotic construction begs for the extension of Price's more technological and adaptive architecture. By considering the relationship between human interaction, sensed input and robotic articulation, proposed in this thesis is a model for architectural robotics that is performative and adaptive as an extension of 'calculated uncertainty'. Working with the industrial robot in the Labatut Lab at the Princeton University School of Architecture Center for Embodied Computation, the thesis presents an argument for a definition of interactivity between users and robots that recognizes the robot as an architectural object capable of simulating experiences of space and augmenting applications of materials in a way that stimulates user feedback. One way that this can be achieved is through the conception of architecture as a human-computer interface (HCI), in which material and space become the medium for communication between the digital and the physical. The industrial robot has huge potential as a mediator for this type of interaction. This extends existing notions of digital fabrication by proposing systems that create a two-way communication of information, as opposed to simply producing digitally designed effects.

This thesis begins with an analysis of some of the important architectural research involving industrial robotics. There are two main approaches to this research, one being construction-centric, and the other based in automated cinematography and animation. In comparing these two fields of projects, we shall find that the robot is essential to each project as a performative object, and we will extract strategies and concepts from each project that lend themselves to a conception of industrial robotics that exploits this performative nature. To further explore how we may extend the abilities of the industrial robot as an architectural tool, the focus of the thesis then shifts towards the historical precedents in the projects of the Architecture Machine Group, Cedric Price, and John and Julia Frazer to help define the ability of architectural concepts to mediate between humans and technology. This lineage finds contemporary motifs in the Tangible Media Group and we will discuss important research in tangible user interfaces and adaptive architecture as a basis for forming a new provocative direction for adaptivity and interaction in architectural design with industrial robots. This new direction is solidified and tested in the third chapter, in which we present three original projects as our contribution to interactive robotic environments. The three projects confront different angles of adaptivity and simulation through material, space, and motion. Using sand as a medium, advanced sensing and communication techniques are used to construct an empowered design space. A final section evaluates these projects against the criteria setup in the previous chapters, and then speculates on the implications of future research in this area.

CHAPTER 1

INDUSTRIAL ROBOTICS IN ARCHITECTURE

A review of the Robotic Fabrication in Architecture publication from 2012 reveals an exclusive focus on six axis industrial robots.[4] Other digital instruments for custom fabrication exist, but the six-axis robot has produced its own field of research. In this chapter, we will survey some of the diverse creative work done with industrial robots, and see that the expressive movements of the robot are essential to each project. However as we shall discuss, there is a disconnect between robotic expression as performance and its usefulness for architecture. The chapter will subsequently discuss the limitations of the robot's expressiveness due to safety concerns and lingering manufacturing practicalities.

Nathan King and Martin Bechtold outline two distinct approaches to the use of industrial robots in architecture in their workshop paper "Design Robotics" from the 2012 Robots in Architecture conference.[5] The first is the pragmatic approach of solving inefficiencies in the building process, and the second is the use of the robot for creative design experimentation, often resulting in complex one-off projects.[6] King and Bechtold then propose a third paradigm, which they call 'design robotics', which "links design innovation to the reality of industrial production".[7] Within this spectrum, we shall shift focus away from industrial mass production, and towards design experimen-

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[4] Rob/Arch 2012, edited by Sigrid Brell-Çokcan and Johannes Braumann.

[5] Bechtold and King, "Design Robotics", 118.

[6] Ibid., 119.

[7] Ibid., 118.

tation. Within design experimentation, there is a general distinction in the way that robotics are conceptualized between those that build and those that animate. This manifests in a cultural difference between Zurich and Los Angeles. These two cultural locales are both producing prominent institutional architecture and robotics research, and although the two cities do not represent the entirety of research in robotic control in architecture, their differences indicate a spectrum of interests that is useful for our discussion. Broadly, in Los Angeles, there is an interest in cinematography, playfulness, and the animation of physical space, and in Zurich a focus on rigorous building technologies and industry. In each, however, the robot is used most often as a means of production. Interactivity and more human-centric actions are discussed sparingly in the current discourse. Human-centric favors actions meant to provoke human *responses*, opposed to a product for humans to *consume*.

The following section examines the contemporary projects and research that span this spectrum from fabrication to film, and finds that between the two styles there is a global trajectory across each project that favors the robot as a performative object, and these performances could be appropriated as a new medium of architectural expression.

CONSTRUCTION

Gramazio & Kohler

The architecture firm and research team of Gramazio & Kohler is one of the few architecture firms in the world that is working with digital instruments from design to construction on the scale of a building. As the heads of the DFAB chair at the ETH in Zurich, Fabio Gramazio and Mathias Kohler are working simultaneously as researchers in the field of fabrication and practicing architects. Specializing in fabrication and design using industrial robotic arms, they are leading the way for robotic architectural production. We shall discuss in depth two projects by Gramazio & Kohler, as well as their writings on architectural robotics, as a slight divergence between the two is revealing as a snapshot of the current discourse, which tends to favor a final product over the architectural system.

In their essay "Digital Materiality in Architecture", Gramazio & Kohler argue that digital fabrication can instill a "sensuality of digital order'" in architecture through its precise and repetitive capabilities.[8] In the same line of thought, they write that the entire process of fabricating or assembling – and its linear expression through programming and code – gives the designer the power to mediate between the digital and physical.[9] Writing

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[8] Gramazio & Kohler, Digital Materiality in Architecture, 7

[9] Ibid., 10

code and designing end-effectors become integral parts of the design process, and instead of designing static plans, "we design a behavior."[10] For Gramazio & Kohler, however, these behaviors are "determined, they have a beginning and an end,"[11] which is a constraint that this thesis will challenge.

For the Venice Biennale of 2008, Gramazio & Kohler developed ROB, a portable container for a large industrial robot arm, in order to bring the robot as a fabrication machine to Venice for on-site production. Gramazio & Kohler designed an installation called Structural Oscillations at the Swiss Pavilion at the Biennale, which was a brick wall that undulated and bent in and out of the rooms of the Pavilion (fig. 1.1). The wall was generated algorithmically to accommodate precise structural logics, as each bend in the wall provided structural support so that the wall could stand alone without being dug into the ground or supported externally. The wall was built entirely by the robot, which applied a glue to each brick before laying it in its calculated location. The completed structure is impressive due to the precision with which the bricks are placed and the subsequent dynamic between each rectilinear brick and monolithic, fluid whole. However, the deployment of ROB was more compelling than the final structure. The ROB unit arrived in Venice by ferry, and was set up outside of the pavilion to begin constructing the wall. ROB is a Kuka KR150 industrial robot, with a reach radius of 2.7 meters, and its immobility forced Gramazio & Kohler to break the fabrica-

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[10] Ibid., 10

[11] Ibid., 10

Fig. 1.1. Structural Oscillations by Gramazio & Kohler at the 2008 Venice Biennale. (Gramazio & Kohler © ETH).

Fig. 1.2. The ROB unit building a section of Structural Oscillations. The deployable unit performs meticulously pre-calculated onsite fabrication. (Gramazio & Kohler © ETH).

tion of the wall into sections (fig. 1.2). The gesture of bringing the robot to the site as a construction tool was important because it provided an efficient and (relatively) convenient solution to the complicated process of custom fabrication, but also, and more importantly, the performative power of a robot became the focus of the project. It is seductive to think of automated technology that can drop into a location and begin creating, just as Archigram theorized with its Instant City.[12] However Structural Oscillations still needed to be assembled by humans. The robot could only fabricate sections of the structure that were within its reach, and then those sections would be moved and placed by workers into the structure. The robot may be the primary point of intrigue for the project, but it is commonly misconceived to be an autonomous builder. This is a part of the reason that robots have not yet been fully accepted into architectural construction, because although it allows for the milling or stacking of complex geometries, most tasks like nailing or gluing are easier to do with humans. There are diminishing returns to meticulously programming robots to do tasks that humans can do intuitively.

Gramazio & Kohler extended this idea with ROB with the Pike Loop project in New York City in 2009, for which ROB was deployed to construct the installation on site. The Pike Loop was similar in formal style to Structural Oscillations; stacked bricks aggregate into a complex surface that ducks and dives up and over itself as one continuous wall. The structure was

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[12] "Archigram", edited by Peter Cook

Fig. 1.3. The ROB unit building Pike Loop by Gramazio & Kohler in NYC. (image from Gramazio and Kohler © ETH)

once again carefully designed to be structurally self-sufficient, and sophisticated stacking algorithms would have been employed to be able to construct the arches that form at the bottom without external supports. Formally however, the structure is less compelling that its older sibling from the Venice Biennale; the structure is smaller, so the resolution of the bricks does not lend as well to a smooth, cohesive whole, and it is less volumetric and cannot be inhabited. However, whereas Structural Oscillations needed to be constructed in sections and next to the site, the Pike Loop was constructed in place, thus strengthening the performative dimension of the project. The ROB unit built sections of Pike Loop within its reach, just like Structural Oscillations, but then the whole unit would shift to the next section, leaving what the robot built as the final product. The images of the fabrication are especially seductive (fig. 1.3); at night, the light emitting from the container

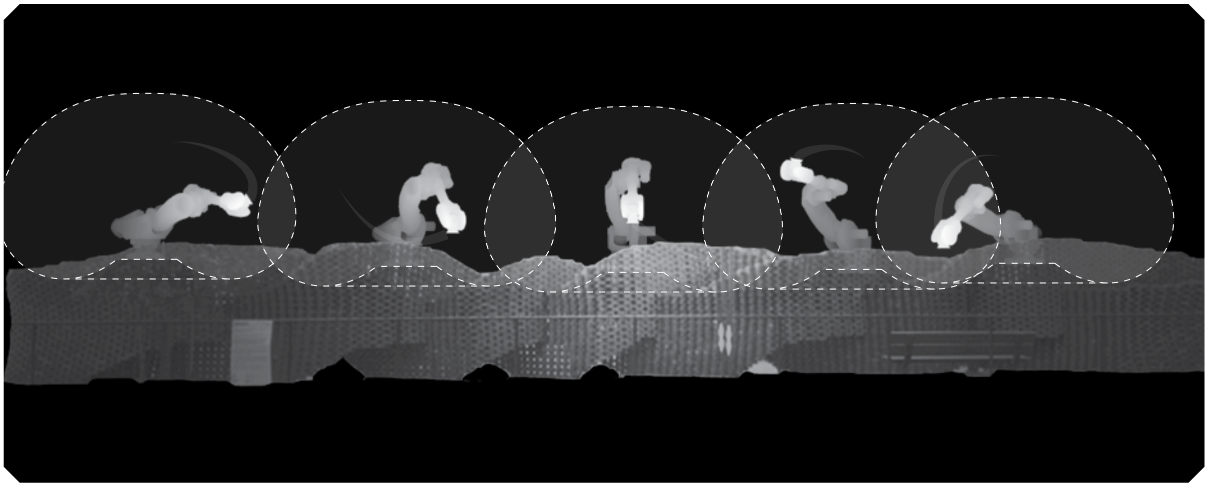

Fig. 1.4. Pike Loop by Gramazio & Kohler reinterpreted as robotic performance. It is unclear whether robotic construction is ultimately practical, or whether the robots themselves hold the fascination. (image by Charles Avis).

to reveal ROB reaching down to place a brick is extraterrestrial and captivating, and gives a mysteriousness to the project that is then entirely lost in the more corroded bricks that remain once ROB is finished. The structure holds intrigue because of the conditions of its construction as opposed to its final formal qualities. Pike Loop is the closest realization to a structure built autonomously by the robot, although it is probable that significant human effort was required to recalibrate the robot each time the units moved to the next piece. Giving the robot mobility is an interesting development, as it begins to break barriers of the standard robot 'cell', and extends its performative envelope (fig. 1.4).

Although Gramazio & Kohler would describe themselves to be in the field of custom fabrication,[13] it is clear that their projects find a new dimen-

[13] Gramazio, The Automatic.

sion in the intrigue of the robotic performance. This is a trend that is not exclusive to Gramazio & Kohler in the discourse of architectural robotics, or robotics in design in general. Flight Assembled Architecture is another Gramazio & Kohler project from 2012 that finds success in the performance of digitally programmed instruments, as three quadcopters fly around a gallery space and slowly pick up and place bricks to create a model tower six meters tall.[14] The project was done in collaboration with Rafaello D'Andrea, who developed the sophisticated control protocols for the quadcopters, and the technicality of the project is a prominent feature. However Gramazio & Kohler acknowledge the quadcopters as "'living' architectural machines" that "complete the composition from their dynamic formation of movement and building performance".[15] However, in these instances and others, there is potential of not only constructing with robotic technologies, but embedding them into an architectural system. There is an opportunity to capitalize on the specificity and precision of digital instruments to create architectural effects that were either previously not feasible, or not considered. The work completed by Gramazio & Kohler displays a trajectory of research in robotics that favors a tectonic architecture. But this result is only the lingering remains of the novel architectural technology, which is in fact the deployment of the robot as an actor upon architecture that can create and manipulate a built environment. This is not to belittle the advancements in custom ro-

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[14] Flight Assembled Architecture, by Gramazio, Kohler, and D'Andrea.

[15] Ibid.

botic fabrication, for these are important in their own right, but instead an identification of an exciting development within the robotics field.

Aggregate Architecture

Achim Menges is the founder of the Institute for Computational Design (ICD) at the University of Stuttgart and has focused his research on digital fabrication and programmed material behaviors in architectural design. Despite Menges' interest in performative materials and systems, his research group's work is interested in producing an architectural product as opposed to a purely performative system, which classifies them within the context of the Zurich-style. However, there are certain trajectories in his research that are of specific interest to this thesis, the most important of which is a project led by Karola Dierichs on the computational modeling and fabrication of granular aggregate structures. As we will later discuss with our proposal for robotic interaction through sand, granular structures are interesting because they provide a more fluid and noisy construction technique that has the potential to be dynamic and interactive.

The Aggregate Architecture project presented at the Robots in Architecture Conference in 2012,[16] and ACADIA in 2013 is a perfect example of a robotic fabrication process that has potential beyond the completion

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[16] Dierichs, Menges, “Robotic Pouring of Aggregate Structures”, 196

Fig. 1.5. Poured Aggregates by Karola Dierichs and Achim Menges is a good example of a construction technique that is empathetic to human adjustment. (image by Dierichs, Menges)

of a static object.[17] The research was conducted by Dierichs and supervised by Menges, and approaches a granular fabrication technique on two fronts. Firstly, the project computationally designs and fabricates custom granular units that interlock when poured to achieve a very steep angle of repose. Secondly, it implements a calculated robotic pouring method to pour the granular units to achieve aggregated forms. The granular units resemble large jacks, for the concavity of the unit increases the friction between each

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[17] Dierichs, “Aggregate Architecture”, 301

Fig. 1.6. For Poured Aggregates, the robot represents the potential for the construct to be repeatably adjusted and replaced (image by Dierichs, Menges).

unit, allowing them to interlock effectively[18]. The pouring is executed by loading jacks onto a tray that is secured the end effector of a six-axis robot, and the robot manipulates the tilt of the tray and its position so that the jacks slide out in a specific arrangement (fig. 1.6). The result is a noisy patterned structural wall that seductively passes light (fig. 1.5). The novelty of designed granular parts – and respective robotic process – to generate a whole is clear, and approaches aggregate construction from the opposite end of the rectilinear brick aggregation methods of Gramazio & Kohler.

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[18] Dierichs and Menges, "Aggregate Structures", 81

The paper published for the ACADIA conference by Dierichs and Menges adds a dimension to the project that is not directly apparent in the built documentation. The argument made for a granular aggregate system is that it presents a concept of fabrication and design that does not rely on static building elements. Dierichs and Menges write, “The relevance of these designed granular systems thus lies in their capacity to enter continuous cycles of erosion and accretion and to allow for adaptive functional grading on the material macro-level”.[19] It is clear that Dierichs is interested in the performative aspects of this system, though it does not seem that such performance features were fully explored. The literature describes how the aggregate walls can be manipulated by a user to create new and custom arrangements. The wall essentially becomes an architectural wall of Jenga.[20] The use of the robot in this scenario then becomes fuzzy; the robotic pouring allows for the construction of relatively precise macro forms, but any user manipulations negate the digital precision of the poured wall. The robot would only become relevant again if the user completely destroys the wall and the aggregates would need to be re-poured. Dierichs and Menges do not indicate that the robot could tend to the wall by making smaller adjustment after the initial pour. If it could, then that would open up interesting possibilities for the aggregate wall to become a continuously evolving structure. The scenario implies a lingering use for the robot, which is not

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[19] Dierichs and Menges, “Aggregate Structures”, 77

[20] The popular game of stacked bricks, in which the goal is to pull bricks out without the whole structure toppling down: http://en.wikipedia.org/wiki/Jenga

explored in the Aggregate project. Although adaptability and performance are written as goals, it seems that the project ends at the creation of a beautifully textured wall.

In the paper published in the Robotic Fabrication in Architecture publication, Dierichs and Menges outline plans to develop an online interactive robot control mechanism.[21] The system constantly scans the poured aggregates to optimize the next end-effector position so that the pouring process can adapt to the uncertainty produced by the falling aggregates.[22] This adaptive system would open opportunities for the robot to accommodate the desired user rearrangements. The online robot control system works by scanning a selected area, determining its highest point, and making that Z-height the new datum for the tool path.[23] It's purpose is to increase the probability that the aggregates will interlock, and would require further development to be able to rearrange granular elements, or sense *why* it should place aggregates in a given location. The robot control system seems to have been implemented in simulation only, but provides a promising trajectory for a simple real-world adaptability in a robotic granular construction.

In a similar manner to the aforementioned Gramazio & Kohler projects, there is emphasis put on the design and construction processes of aggregated parts, but there is a present yet unfulfilled dimension of continuing change in each project. Both of these leaders in the design and construction

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[21] Dierichs, Schwinn and Menges, “Robotic Pouring of Aggregate Structures”, 200-201.

[22] Ibid.

[23] Ibid., 202-203.

fields of architectural robotics are clearly considering the role of the human as manipulator, but have not yet confronted the spatial power of the robotic performance and its implication for user interactions. To be sure, there is merit in using the robot as a tool for producing, but as the above projects show, the robots are more performative than the architects may realize. The following projects are considered Los Angeles-style, and do consider the performative power of the robot. However, we shall find that pure robotic performance opens up new opportunities for interactivity that are yet unrealized.

ANIMATION

The Los Angeles style projects discussed below are more explicitly interested in robotic performance than the projects discussed above. Ranging from cinematography to animation to augmented reality, the main criteria for this category of projects is that the contribution is ultimately representational. To 'fabricate' can mean to invent or concoct a deceitful scheme, and although deceitfulness is unnecessarily derogatory, it is an interesting way of perceiving these projects as 'digital fabrication'. Through software developments and the nature of the projects, these projects achieve physical manifestations of digital animations. We will look with care at the role of the user or audience in these scenarios, as well as the overlapping interests and trajectories with the construction projects.

SCI-Arc and Esperant.o

One of the most prominent institutions for robotic architectural practices in Los Angeles is the Southern California Institute for Architecture (SCI-Arc), where the Robot House has five Staübli robots synced by custom software. Esperant.o is the plug-in developed by Brandon Kruysman and Jonathan Proto for the AutoDesk animation software Maya. The Python script enables a robot to be rigged in the animation software, and thus simulated through the animation environment.[24] Furthermore, the simulation can calculate code for the Staübli robots from the motor angles of the simulation, allowing the animation environment to graphically produce real robot movements. This enables the keyframe system of timing that Maya runs on as a way of controlling robotic movements. By setting the position of the robot at different keyframes, and then running through the keyframes at 24 fps (as is standard in the Maya software), the robot can be controlled in real space the same way that animations are controlled in the digital space. Kruysman and Proto complemented this software with another that they call Charla, which tracks the motion of the robots in order to better sync the movements in real space with the timing from Maya.[25] This software was developed and implemented at the Robot House at SCI-Arc, and the result is an achieved synchronous movement between each robot in the space. What this affords

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[24] Kruysman and Proto, “Augmented Fabrications”, 78.

[25] Ibid.

Fig. 1.7. Augmented Fabrication by Kruysmans and Proto is an animation-based simulation of robotic movements and tool paths. The synchronisation of robots, cameras, and digital simulations opens up possibilities for architectural applications beyond the mere making of objects.

designers is access to processes that require multiple actuators and sensors, as well as an interface in Maya that is standard across animation and cinematographic fields. Furthermore, robot programming and simulation occur simultaneously in the animation software, which has led to the realization of 'Augmented Fabrication', in which simulation data and real-time images are composited to display feedback about robotic toolpaths (fig. 1.7).[26]

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[26] Kruysman and Proto, "Impossible Objects", 110-111.

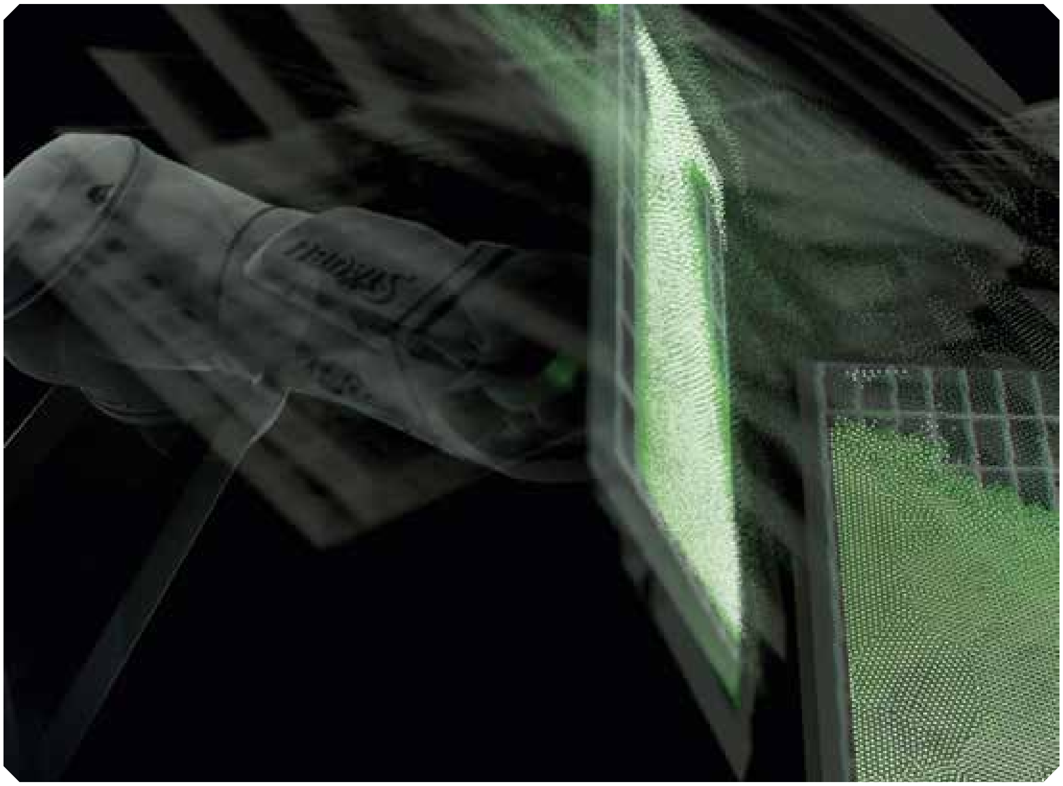

Fig. 1.8. Projection Mapping on Moving Objects by Kruysmans and Proto is another example of sophisticated synchronizations of multiple systems. The potential for this concept to become a tool or means of architecture depends on its integration of human interaction.

The software enables the resulting projects to push the limits of architectural representation and robot control. Kruysman and Proto write, “By combining robotic motion control with animation techniques, the two-dimensional flatness of the screen is challenged, opening up new potentials in image-making that extend beyond the flat screen into hybrid realities where the production of representation and the representation itself become blurred”.[27] Synchronous Dissections is a workshop from the summer of 2012

[27] Ibid.,108.

that explored this new potential in image-making; by attaching boards, each with four LED lights, to the end of four robots, and then using a fifth to hold a camera taking long exposure photographs, three-dimensional light sculptures emerged as all five robots moved in sync with the exposure of the robotically controlled camera. The power of esperant.o and Charla is apparent, but the final effect of the sophisticated synchronization exists only in the digital space through the composited video (fig. 1.9). The syncing of camera shutters and animated robots was the primary technological focus[28] but perhaps through increased robotic speed and head tracking technology, the effect could be more active in real space.

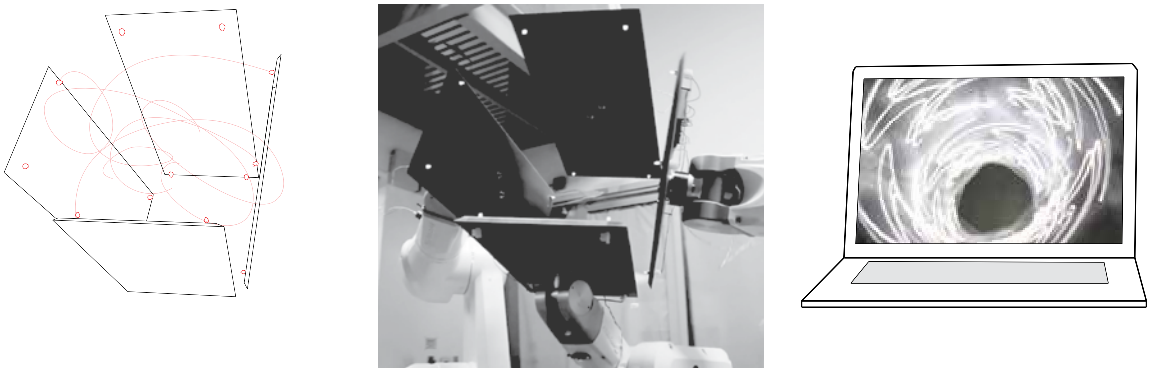

Fig. 1.9. SCI-Arc's Synchronous Dissections. Cinematic robotics concentrates on heavy post-production of images. How can this style of robotics establish itself in real space? (photos from Synchronous Dissections video by Kruysman and Proto).

Full Turn, a project by Benjamin Muzzin at ECAL, in which LED screens strapped back to back spin quickly enough to construct a three-di-

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[28] Proto, Personal Interview.

mensional image in real time, achieves a holographic effect that Synchronous Dissections does not.[29] However robust synchronization technology is certainly an important aspect to any robotic project, and opens possibilities for adaptability. What if robots didn't just synchronize with each other, but also with the human movements in the same space?

In another project 'Projection Mapping on Moving Objects', done in 2012, a particle simulation was projected on screens held by the Robot House Stäubli robots, and as the robots moved the screens, the particle simulation reacted as if the robot movement was agitating the particles (fig. 1.8). The screens occupy and move through three-dimensional space, and the adjusting visuals become an analytical tool for real movement. Simulation and physical movement are wedded in real space. Although the project was only intended as a demonstration of synchronized projection and movement,[30] it suggests an interesting direction for robotic interaction that introduces movement into a computed space. Like the Urban Planning Workbench by Hiroshi Ishii and John Underkoffler,[31] in which a projection on a table of objects delivers visual data such as wind and shading analysis, projecting on robotically articulated objects offers a new opportunity for design prototyping. For any application that depends on an objects orientation, such as the sun glare off a surface at certain orientations, or optimizing orientation for drainage or shading, this synchronized system could be a powerful analytical

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[29] Muzzin, "Full Turn".

[30] Ibid.

[31] Ishii and Underkoffler et al, "Augmented Urban Planning Workbench".

tool. Integrating sensing and safety measures could realize these interaction ideals. It could also become a future of three dimensional entertainment media, as gaming or film could react to the movements. The ability to combine abstracted physical properties and digital information in real space is still, however, largely unexplored. The mobile projection mapping is in part compelling due to the achievement in coordination between software (visuals, motion, and projection mapping), but also in the effectual power of the digital and real meeting in real space. As we shall see, Bot & Dolly, where both Kruysman and Proto currently work, has taken the robotic projection mapping to the next level of performance, continuing the concept towards the sophisticated production of a short film.

Bot & Dolly Box

The research from the SCI-Arc Robot House may be inspired by cinematography, but Bot & Dolly is fully dedicated to it. Bot & Dolly is a creative studio in San Francisco that specializes in automated cinematography, and the company grew out of the development of the Iris robotic control system, which was used to film the move *Gravity.*[32] Although the robots do not feature as objects in *Gravity,* Bot & Dolly has made a concerted creative effort to push the envelope of industrial robot performances to its limit. The studio's short film *Box* came out in October of 2013, which featured two Kuka

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[32] Gravity, directed by Alfonso Cuaron.

KR150 robots moving screens in sync with projected graphics and a human actor, resulting in a short 5 minute film (fig. 1.10).[33] The whole scene is shot in one take with no CGI after effects. A third robot holds a camera behind the scenes, and the projected graphics are rendered to the perspective of the robotically controlled camera, so the whole scene comes alive in perfect sync.

Box consists of five chapters, each pertaining to a type of magic or illusion,[34] and illusion is the prevailing effect of the project. The perfectly synchronized movements and rendered images challenge one's perception and sense of reality. To some extent, it is hardly reality, as the images only appear so compelling if viewed from the point that the images are rendered from. Thus the primary critique of *Box* is that not all viewers in a live setting would get the benefit of the illusionary perspectives. However, having had the privilege to see the demo in person, the carefully calibrated illusionary tricks are dwarfed by the speed and power of the two robots whizzing through the space. The cinematographic tricks are impressive to be sure, but watching the actor interact in the same space as the KR150s, and the feeling of being in the same space as the performance itself, render the specific perspective as superfluous. Industrial robots always require protective work cells as a safety measure, but Bot & Dolly has begun to erase the boundaries between viewer and robot. It would be beneficial, then, to consider how a performance like *Box* can engage with the space that it inhabits that does

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[33] Gottlieb et al, Box.

[34] The five types of magic in Box are Transformation, Levitation, Intersection, Teleportation, and Escape.

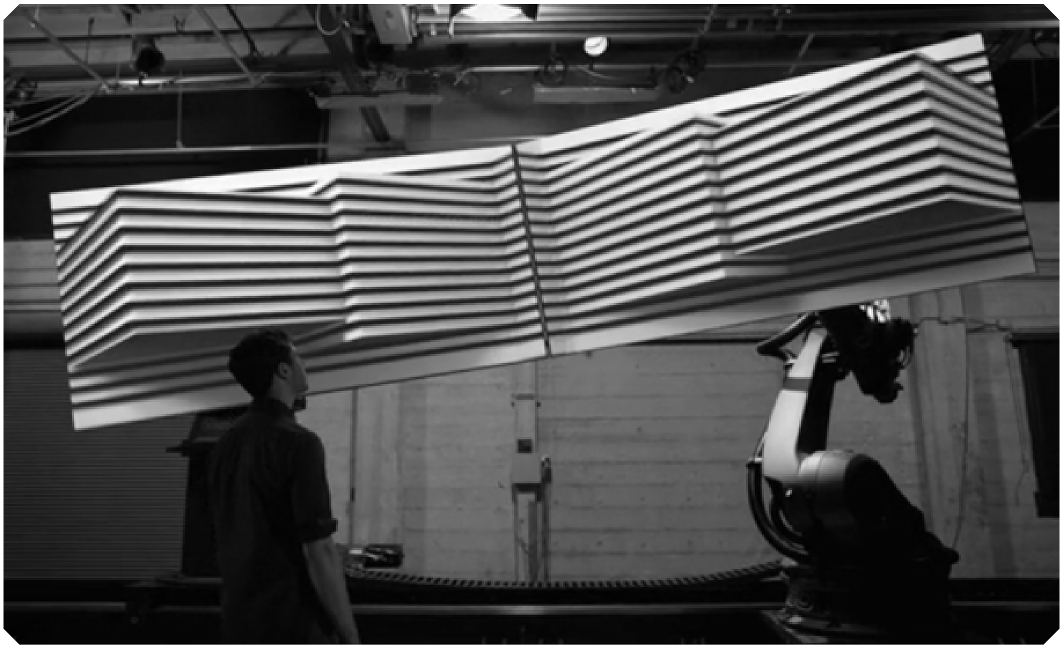

Fig. 1.10. Bot & Dolly's *Box* takes projection mapping on robots into the entertainment space with perfectly synchronized movements and graphics. Each graphic is rendered from the specific perspective of the camera, giving the full effect to only one person.

not require specifically rendered perspectives. I propose in a later chapter a project that takes advantage of this spatial phenomenon by using the robot to delineate space based on the geometric qualities of the room. The spatial delineations can be exploited as a parametric design tool, allowing spatial dimensions to be rapidly prototyped through a simple parametric interface. Each robot in *Box*, with its 4' x 8' surface end-effector, similarly creates a spatial experience, but more like a dancer than a piece of architecture.

Box is purely a performance, and is not intended to adapt to human involvement (the actor's part is carefully choreographed), but if its elements were to become a more permanent installation as part of architecture, the setup could be a stimulating performance or an analytical tool. Instead of producing a well coordinated, one-off video, what would it take for *Box* to be useful as a permanent architectural object? It would need to produce something novel with each interaction, which would require a feedback loop of a sensed environment, and perhaps a more personal touch, such as head-tracking the users in the room with an Xbox Kinect and rendering the visuals to that person's perspective. Box already pushes the limits of technical feasibility, and introducing a feedback loop certainly increases the complexity, but both the sensing technology and robotic control exist and can be interfaced. The synchronization of light, movement, and space should not be confined to the performance space, and the same concepts could have important implications if translated into design tools or real architectural space.

Bot & Dolly is not only producing their own projects, but empowering designers with their software as well. They recently outfit the UCLA SupraStudio with Kuka robots and their Maya-based control system, effectively eliminating the barrier to entry for controlling the robots.

Super Aero Robo Spatial

Greg Lynn's new studio at the UCLA SupraStudio, entitled Super Aero Robo Spatial, is the recent and fresh exploration into the industrial robot as a part of the architectural design process. The studio situates itself conceptually between the literal and phenomenal movement of architectural ele-

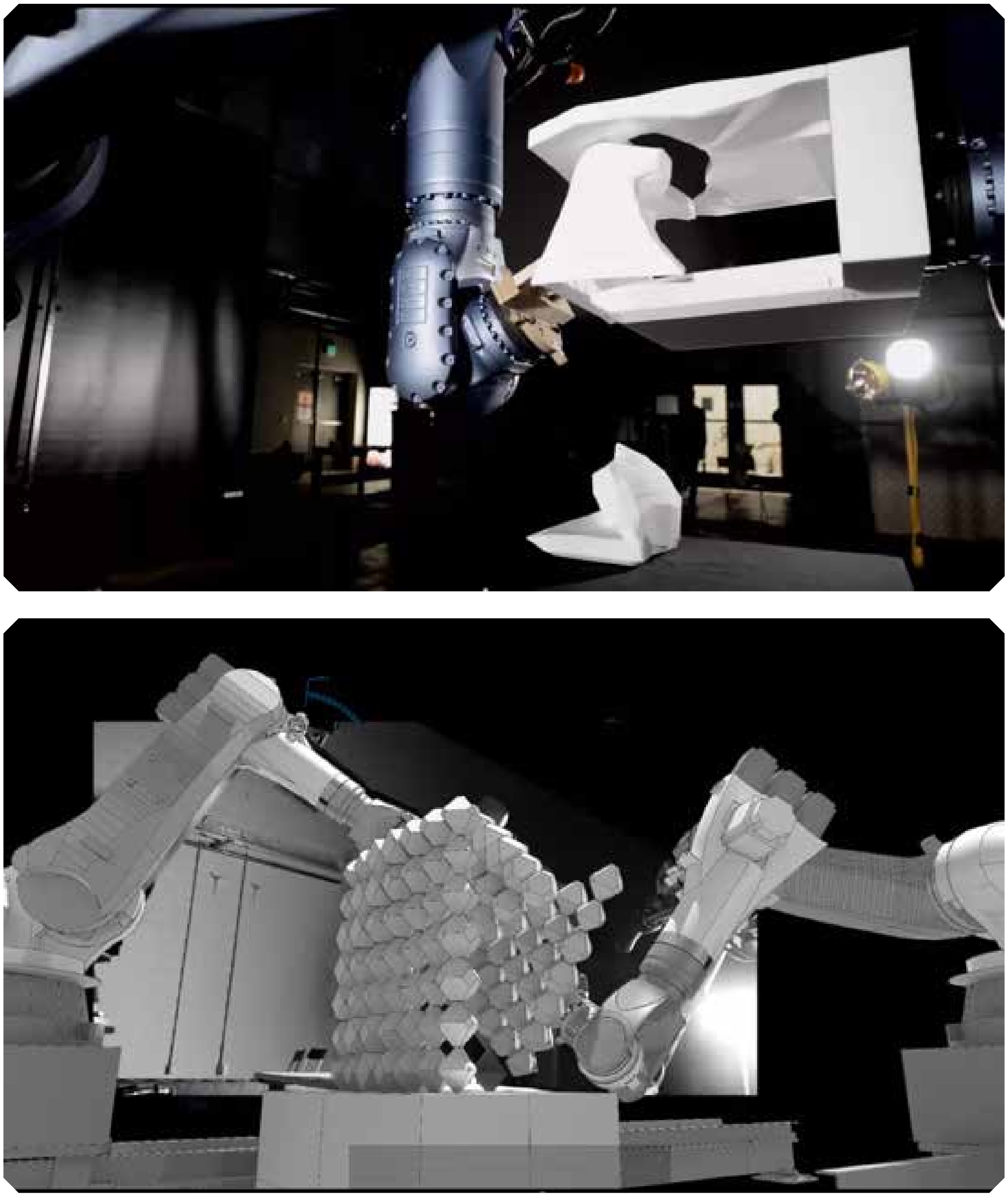

Fig. 1.11. Greg Lynn's SuperAeroRoboSpatial works with robots to move model parts, theorizing about large scale architectural movement. In these projects, there is a there is serious consideration given to a future architecture with house-sized moving parts. (Image from Suprastudio Student Reel).

ments.[35] The students use the robot to literally move formal elements around at the model scale, manipulating designed forms that play with light, volume, and surface. In one student project, two robots move façade aggregations to create changing patterns of light, and in another, the robot picks up and moves specially designed interlocking units (fig. 1.11). The projects are provocative, with the designed forms that reflect the literal movement actuated by the robot, as well as the implication of a large-scale robotic system that could manipulate full-scale structures. Lynn writes in Animate Form that "although the form of a boat hull is designed to anticipate motion, there is no expectation that its shape will change. An ethics of motion neither implies nor precludes literal motion".[36] Lynn has now expanded the expectation of robotic performance in architecture to include the specific design and formal envelopes of the building itself. His studio demonstrates how cinematic robotic motion affects the form of buildings. Even though Lynn is coming from a distinctly cinematic approach to this problem, it is not all that different from the work by Gramazio & Kohler that pushes the envelope of architectural design with industrial robots. Both are considering what new architectural forms can be conceived by the articulated motion of robotics.

It is not entirely clear with the first round of RoboSpatial projects what this approach to architectural design means for architecture. To some

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[35] "Greg Lynn Suprastudio".

[36] Lynn, Animate Form, 10.

extent, considering a future with giant, house-sized robots that rearrange building elements is the most powerful theme evoked in the project. It is a radically different approach to architectural design with robots than any other concept we have discussed this far. One-off fabrications or viral videos are not present, and instead there is a serious consideration for a future architecture with embedded robotics. Because each project is done on a model scale, it considers only formal arrangements, and skips over any details of the mechanism for movement, or what these spaces may feel like to inhabit. The studio doesn't (yet) ask questions about what a revolving room and or self-rearranging building cluster would actually do or feel like. Although this is just the beginning of an otherwise useful speculation on new building forms, the industrial robots at present are able to articulate spaces on the human scale. Between this speculative research and the more practical Zurich-style projects, there is a space that the robots can develop that is grounded in real experiential feedback, yet abstracted to a point that allows wiggle room for speculation.

Augmented Materiality

As we have seen, these Los Angeles projects are highly performative and animate real space, but are still mostly concerned with the production of images or objects without considering how they might augment space itself. Lynn's studio is confined to the model scale, although the models begin to deal with such issues. The combination of media and motion from SCI-Arc and Bot & Dolly has many exciting possibilities, but it is still unclear as to what role a human can play once the code has been run. What does interactivity truly look like in these projects?

There is research by Ryan Johns that begins to synthesize technologies to explore solutions to this problem. In his paper Augmented Materiality, Johns outlines new workflows that combine augmented reality, digital simulation, and robotic actuation.[37] Johns maps projections to work objects with head-tracked perspective, allowing the designer to see a three-dimensional representation of the object being made and robot's future toolpaths on the actual material itself (fig. 1.12). Johns also includes more tangible interactions, allowing the designer to place blocks to indicate structural loads, and draw on the material to indicate areas that should be removed. One setup for Augmented Materiality employs the stochastic material process of melting wax, in which an Xbox Kinect on the end of the robot scans the wax block and identifies areas on the block that have an excess of material based on an underlying digital model.[38] The robot then melts the wax from the identified areas; the process is executed iteratively until the wax block takes the form of the underlying digital model.[39] Johns concludes that, "... the process cannot proceed without the simultaneous cooperation of its four players: the human designer, the robotic manipulator, the computer simu-

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[37] Johns, "Augmented Materiality".

[38] Ibid.

[39] Ibid.

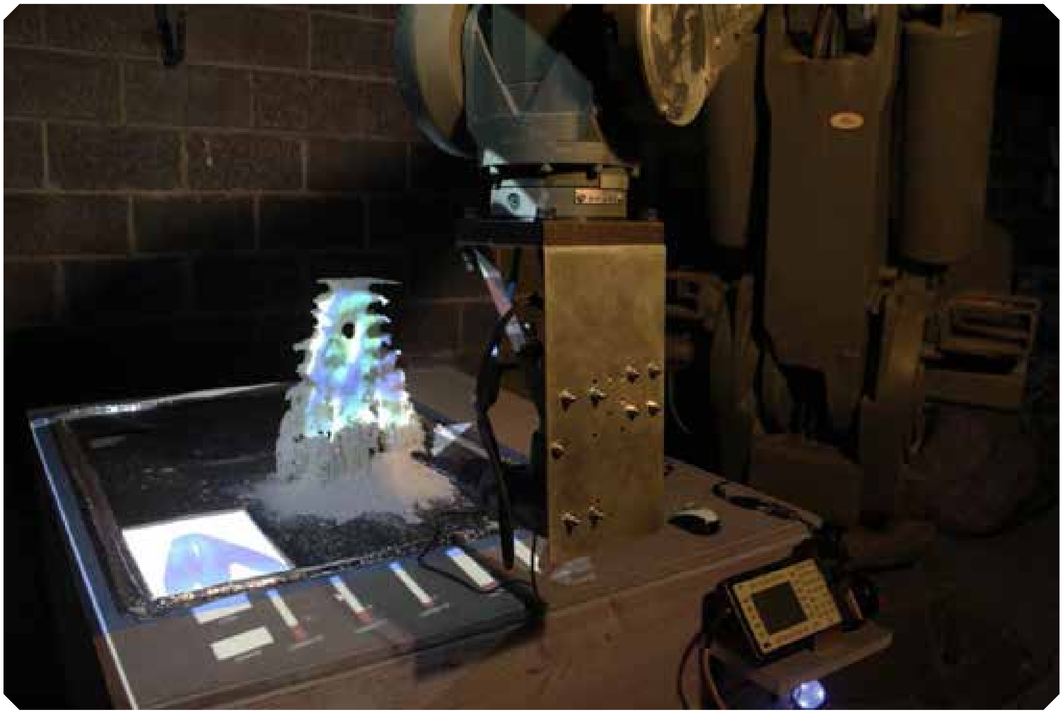

Fig. 1.12. Augmented Materiality by Ryan Johns enhances collaboration with robots through augmented reality, digital simulation, and tangible interfacing techniques. (photo by Ryan Johns).

lation, and the material reaction."[40] The success of Augmented Materiality is in the representation of digital information to bring design decisions into the fabrication process. This work will be influential to the contribution we present in Chapter 3, and will extend Augmented Materiality by focusing on interactions with the material itself without the aid of augmented reality.

Let us now turn to observations of pedagogy and industry with the industrial robot, in which we will define and discuss some constraints that exist for designers using industrial robots.

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[40] Ibid.

PEDAGOGICAL OBSERVATIONS

I traveled to Zurich in January of 2014 to observe the work being done there, and the following observations stem from that trip and subsequent interviews conducted. Being on site to see the working process and influences was instrumental in understanding the motivations and trajectories of the research culture. The Department of Architecture at the ETH-Zurich supports a relatively small number of research groups working in computational design fields, Gramazio & Kohler being the specialists in robotic construction processes. I was able to participate in the fabrication workshop run by the DFAB chair during the month of January.

The workshop that I attended was one of a number of a month-long design or fabrication workshops that students are required to take between terms in order to graduate. The structure of the workshop is that the research assistants develop design constraints for the students based on the research topic and fabrication assembly process. At this particular workshop, the project was to build an acoustic wall made of PVC pipes that were robotically cut and placed to form acoustically and visually interesting façades. The project is called Depth Modulations.[41] The workshop was an extension of a research group that is collaborating with the REHAU Vertriebs AG to fabricate novel synthetic acoustic materials. Collaborations are important to the work of Gramazio & Kohler, and many of the novel processes developed

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[41] Gramazio & Kohler, “Depth Modulations”.

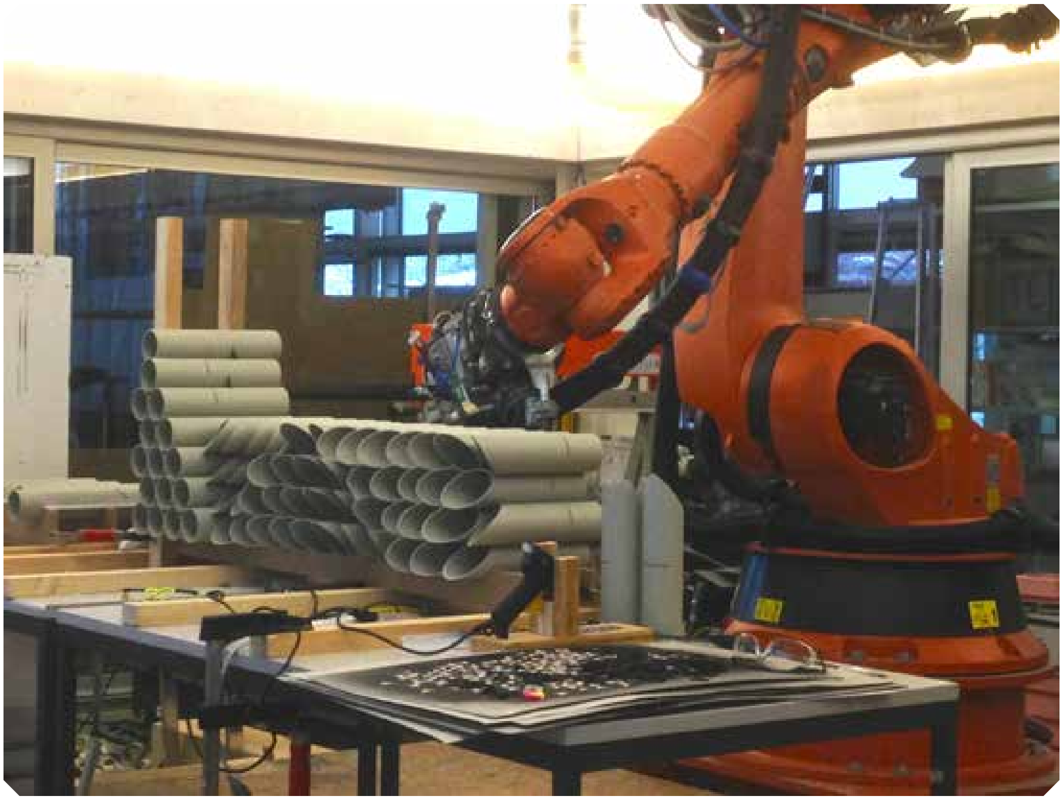

Fig. 1.13. The workspace at the Digital Fabrication lab at the ETH Zurich. The student project is to design acoustic walls controlling three parameters that the robot can manipulate (tube angle, tube length, cut angle). (photo by Charles Avis).

in research are results of these collaborations, such as the Flight-Assembled Architecture, and the more current Dynamic Concrete Casting (fig. 1.15).

This particular workshop on acoustics, being a student workshop, was only using the robot to control three parameters: the angle the PVC pipe was cut, the rotation of the pipe upon placement, and the translation placement of the pipe (fig. 1.13). The student projects that I saw did not push the envelope of novel fabrication methods, nor algorithmic acoustic scripting. No less than four students had to be on an assembly line to do the

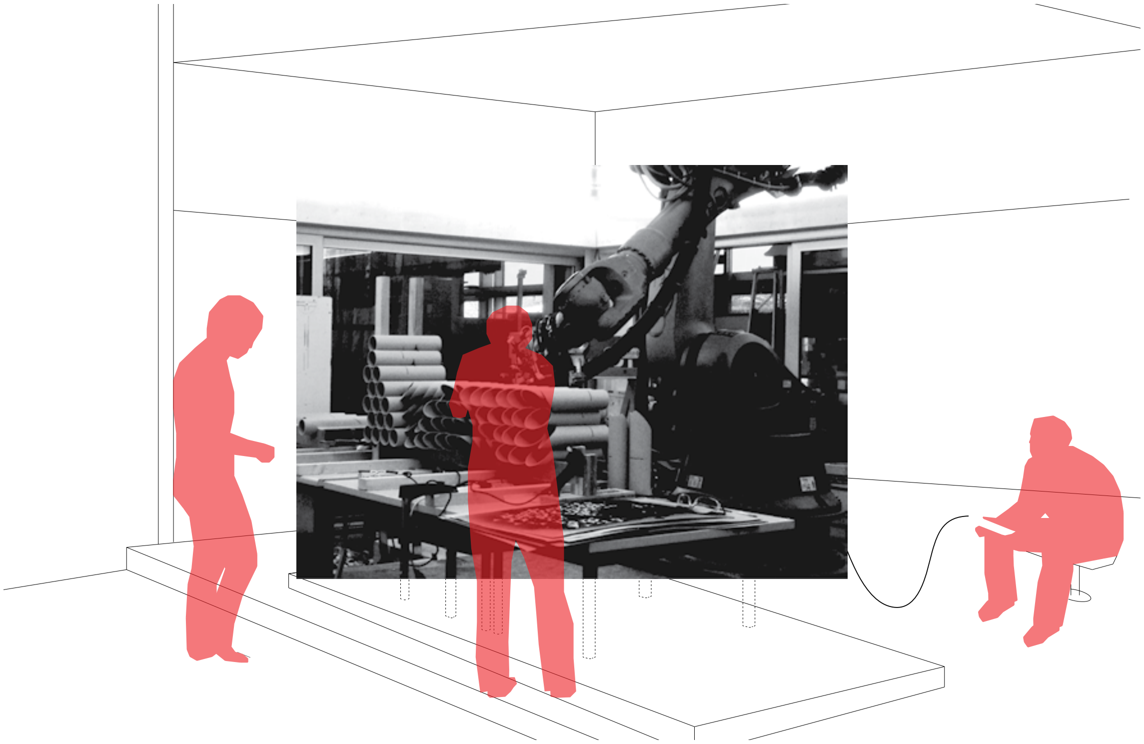

Fig. 1.14. Behind many (if not all) robotic fabrication projects is a considerable amount of human grunt work. At the ETH, tasks like gluing and sanding had to be done by students. (image by Charles Avis).

tasks of gluing and sanding that the robot was not programmed to do (fig. 1.14). However the exercise is of interest for two reasons:

Firstly, the barriers to entry for designing robotic fabrication processes are generally very high, and the workshop acknowledged this by significantly constraining the parameters that the students had control of. This is precisely relevant to user and designer interaction with robotic systems because initial constraints enable a less-technical consideration of design with robots. The students that I spoke to were able to talk me through

Fig. 1.15. Dynamic Concrete Casting by Gramazio & Kohler has very real construction potentials (Gramazio & Kohler © ETH).

elaborate design narratives over the manipulations of just three variables. The fabrication process, as well as the chosen material, generated the design constraints, and although this enabled a wider range of users, it was still dependent on the experiment design by the research assistants.

Secondly, it was interesting to see the decisions made in the fabrication process to optimize efficiency. The process was by no means automated; the robot would pick up a correctly sized (and pre-cut) PVC pipe, and swing it around to the table saw, on which it would place the pipe at the correct angle and rotation to be cut. A student would then pull a string attached to the table saw blade in order to cut through the pipe, after which the robot operator would move on to the next command. The robot would place the newly cut piece in its correct location in the stack of PVC pipe, and then the assembly-line would start; two students would glue the piece to its neighbors, and another would clean it out. In the end, it took about 1 minute to finish one PVC pipe. It perhaps would have been interesting to witness the previously discussed state of the art methods of the DFAB research, such as Smart Dynamic Casting[42] or the Aerial Constructions[43], however the pedagogical simplifications are, in a way, more useful for the immediate purpose of this thesis. By further simplifying the interactions with the robot, a wider user base and more collaborative environment can be achieved. But from this experience it is clear that systems need to be developed to break from assembly-line production. Ryan John's Augmented Materiality, for example, is one example of a process divergent from linear determinacy in fabrication.[44]

The fabrication of these student walls was, I perceived, exciting for the students as a realization of their digital work, but at the same time mundane and boring. Certainly the most exciting moment was when the table saw shield broke and dropped into the blade, which sent it flying across the room, thankfully not hurting anyone. It is called 'robotic fabrication', but it is robotic in the same way that people would demeaningly call someone

[42] Gramazio & Kohler, "Smart Dynamic Casting".

[43] Gramazio & Kohler, "Aerial Constructions".

[44] Johns, "Augmented Materiality".

lacking in personality ‘robotic’. The machine is, generally, the same as those used by Bot and Dolly[45], yet it is striking how the experiences differ. The focus at the DFAB remains on novel building, which is linear and repetitive.

This Zurich-style pragmatism seems to stem from two influences: the first is the pedagogical atmosphere of the ETH Zurich. The HIF-Building at the ETH, in which the robot unit is housed, is a large warehouse, filled in each corner with massive steel cable and concrete stress testers, which are operated by the Civil Engineering department. The robot unit pales in comparison. It almost hides in the corner within its container. Phillipe Block, of the Block Research Group at the ETH shed light on the implications of this space, which is that it is indicative of the influence of the applicable approach of civil engineering in the architecture department. One of the architecture students remarked that the civil engineers view the architecture work to be too conceptual. In the discourse of robots in architecture the ETH has produced some of the most pragmatic and engineered projects of anyone in the world, and it is clear standing in the shared warehouse space how that influence comes about. The second influence is a consideration of industrial requirements.

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[45] The Kuka KR150 model, with a payload of 150kg.

LEARNING FROM INDUSTRY REQUIREMENTS

Industry plays another key role in the influence of Zurich-style robotics projects. I visited Tobias Bonwetsch and Ralph Bärtschi of ROB Technologies, who are working on software to allow for the robots to become more easily adaptable to new tasks. The impetus behind this development is to work with small and medium sized companies that cannot maximize the potential of robots. Industrial robots are designed for repetitive single use, (which is in part why it is so challenging to hack them with meaningful adaptability), and ROB Technologies sees a potential market in building tools to ease the transition from one single use to another. ROB is a spinoff of Gramazio & Kohler in order to capitalize on this business potential. This is particularly interesting because it begins to confront the changing use-cases of industrial robots. Mr. Bonwetsch believes that ‘service’ robots, or robot arms embedded in the household for various tasks, will become a reality before their target industries begin to adopt them.[46] The problem of rapidly adapting uses is the first obstacle in making robots deployable into smaller scale establishments.

Another key issue that is relevant to all designers, creatives, and industries working with industrial robots is safety. The re-purposing of a robot work cell to produce a new product creates a multitude of safety issues that people like Mr. Bonwetsch and Mr. Bärtschi are working towards

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[46] Bonwetsch and Bärtschi, Personal Interview.

minimizing. On a permanent production line, like at Tesla Motors or Ford, the robots are contained inside of safety fencing and there are clear demarcations, and since each robot has one task to repeat constantly, little intervention is required inside of the reach envelope of the robot. Small industries and designers would require much more flexibility, and flexibility requires re-calibrations of workspaces, end-effectors, and the generation of new code, which in turn requires working within the reach envelope of the robot and supervising the new processes to identify and fix errors. Smaller projects force humans to interact more often and more closely with the robot processes because of the ubiquitous challenge of synchronizing and calibrating each operation of the robot. A video of the Tesla factory, for example, shows rows of robots and vast pressing machines all calibrated to the same space, passing work objects, and working with minimal human intervention and maximal efficiency.[47] At the DFAB at the ETH, however, the student projects cannot afford the time or money to achieve the external automation, and thus try to strike a balance between the automation strength of the robot and the human interactions. Instead of spending hours programming the robot to apply glue to the structures, not to mention developing the second end-effector that shoots a glue gun, the simple and fast solution was to allow the student to enter the robot space and glue it himself.

To keep these scenarios safe, ROB Technologies is building safety checks into their software, but does not possess control over the safety proto-

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[47] "Tesla Motors Part 1: Behind the scenes of how the Tesla Model S is made."

cols built into the robot system, or hardware safety precautions in the robot work cell. For the time being, safety cannot be quickly bypassed when dealing with industrial robots, which limits the possible uses in non-industrial settings. From observation at the ETH, the Princeton University Embodied Computation Lab, and at Bot & Dolly in San Francisco, the two factors that are necessary for a safe robotic environment are predictable movements and pre-determined choreography. Predictable movements can be achieved in the design process by digital simulation software, such as ABB's Robot Studio, and Bot & Dolly's BDMove, and each move is then run through a dress rehearsal on the real robot at significantly reduced speed.

Clearly, in any scenario that would involve an industrial robot as an intimate presence in architecture, as is a consideration of this thesis, safety is a primary concern, and it seems impractical to run through dress-rehearsals of every robotic movement before it is executed. The ABB headquarters had a installation in its front lobby that offers one solution to this problem. The installation was an ABB six-axis robot that would take visitor's coats and arrange them on a rack. It was contained in a cell with glass walls, and a little window through which one could put their coat on a hanger. With the activation of an RFID tag, the robot would then grab the hanger and place it on a rack. Scanning the RFID tag upon the visitor's exit would trigger the robot to grab the visitor's coat and return it to the window. The setup is simple and not a fluidly adapting process as is the interest here, however the concept of setting up interactions with a robot through a constrained space provides a simple solution to a robot as architectural object.

In this chapter, we have seen a wide spectrum of projects that use the industrial robot for real construction, experimental construction, film, and architectural design. The key trend is that each project fits within the paradigm of robot-as-producer. The performative and precise movements of the robot are used as a means to an end, which is often a sleek custom product or viral YouTube video. The work with the robots has the potential to be productive on more continuously evolving projects, but there are many advancements to be made in this area.

As we will discuss in the following chapter, considering the interactions between users, designers and robots, and how they can communicate through physical materials, provides a reframing of these current trajectories of research. Beginning as early as 1960, Cedric Price, John Frazer, and Nicholas Negroponte were considering the problem of the embodiment of technology in architecture simultaneously with developments in Human Computer Interfaces. The development of material user interfaces requires continuous action from both robot and human, and has not been fully explored in robotic architectural research, as has been demonstrated in this chapter.

CHAPTER 2

HUMAN-ARCHITECTURE COMPUTER INTERACTION

As we have seen, industrial robotic research tends to display strong performative qualities. So what if these performances were taken even further to become persistent objects of architecture themselves? In what way can an industrial robot contribute architecturally in its own right? Conceptually, performing robotics in architecture is not and should not be limited to industrial robots, however it will prove fruitful to continue evaluating the industrial robot due to the questions of its use raised thus far.

There are significant precedents in architecture that work towards a deployment of robotics within an architectural system, and contrasting these projects with the current fabrication discourse reveals a similar use of robots to manipulate space, but to a different end and by a different means. This discussion begins in the late 1960s, with Cedric Price and the Architecture Machine Group (AMG) at MIT. Price's 'Generator' (1976) and AMG's 'Seek' (1970) were designs for systems in which a central mechanical agent rearranged blocks into arrangements dictated by a central computer. At the time, computing power was limited but growing (the first mass marketable personal computer, the Commodore PET, was available in 1977), and as a result there was a substantial interest not just in how architecture could be affected by computing, but also how humans and computers could interact. Architect Nicholas Negroponte of AMG wrote extensively on human-computer interaction (HCI),[48] and to an extent it was indistinguishable from

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[48] Negroponte, Digital Being.

the discussion of architecture and computation because the focus was on "externalized computation" by embedding objects with sensors.[49] 'Generator' and 'Seek' present systems that use information technologies to continuously manipulate boxes to change the nature of a space. Both of these projects are essential to our discussion of calculated uncertainty, as they are two of the first architectural designs that employ computational algorithms to update and respond to inputs and measured data.

This section will discuss a lineage of historical projects that are important to a discourse on computationally informed spaces. In parallel with the development of computer graphics and HCI, these projects mark out a different conception of computational interaction, which we may call Human-Architecture-Computer Interaction (HACI). The architects for each of these projects conceptualizes architecture as the medium of computational input and output. Computation enables indirect and direct user input, and choreographs an architectural response.

SEEK

The Architecture Machine Group at MIT, led by Nicholas Negroponte and Leon B. Groisser, developed 'Seek' for the 'Software' exhibition at the Jewish Museum in New York in 1970 (fig. 2.1).[50] Seek is a computer and actu-

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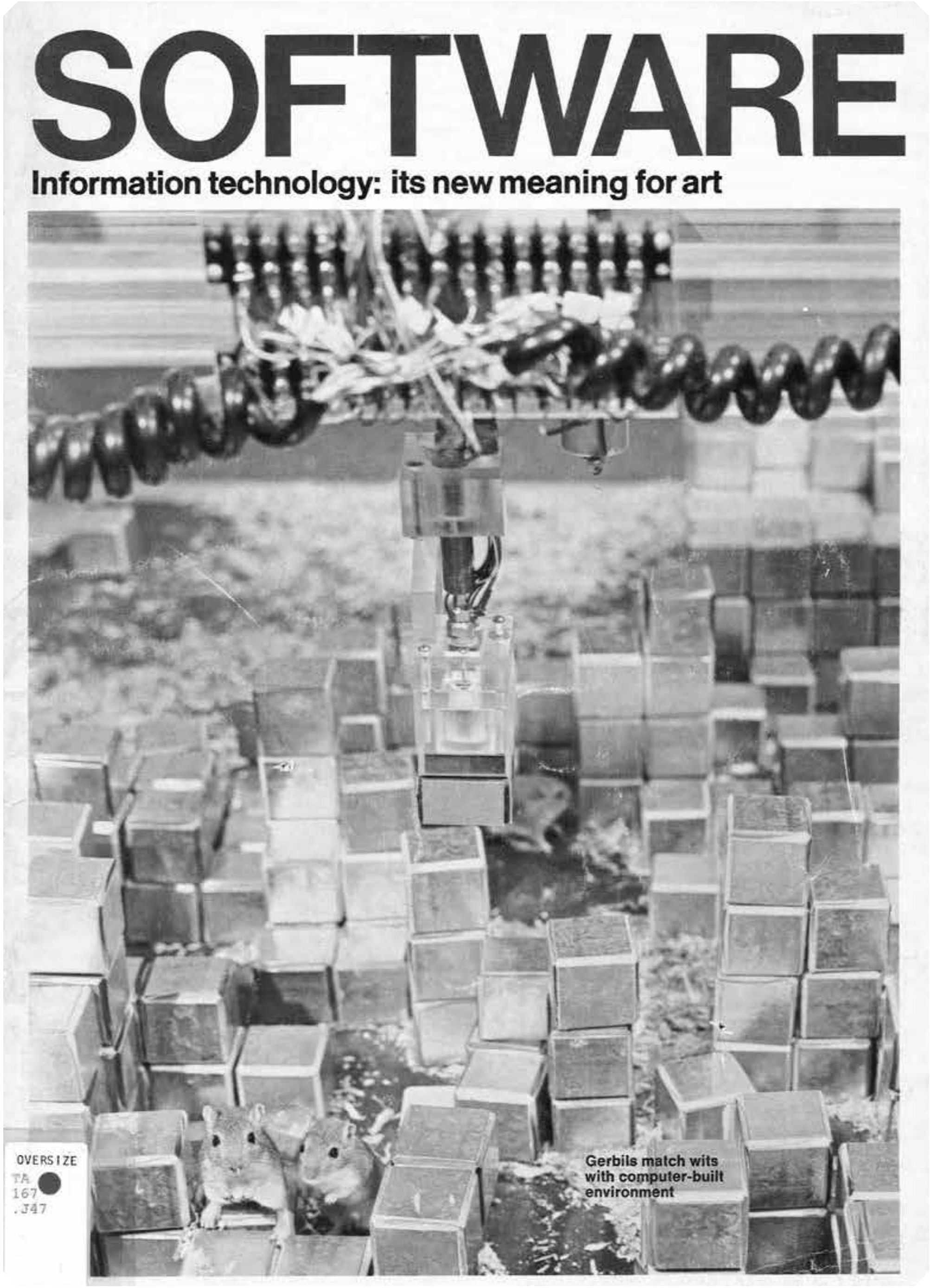
[49] Negroponte, Personal Interview.

[50] SOFTWARE Information Technology, 23



SOFTWARE

Information technology: its new meaning for art

Gerbils match wits with computer-built environment

Fig. 2.1. As an art installation, Seek pushed the boundaries of externalized computation and adaptive architectural systems (image from SOFTWARE catalog).

ator that senses the location of toy blocks, and rearranges them within its context. The installation for the exhibit was a large, 5' x 8' glass box, in which gerbils were placed to interact with the toy blocks. The gerbils would topple, nudge, and rearrange the blocks, and Seek had to recognize the position changes of the blocks, and then 'tidy up' the displaced blocks.[51] Slight displacements by the gerbils prompted the robot to put the block back in its original place, but more substantial displacements were seen as intentional, and thus reoriented in their new location to match the grid.[52] The environment was one of the first computationally adaptive environments, in which sensing and computation could adapt to the unpredictable inputs of animals. Negroponte's work at the time "externalized computation"[53] to expand interfaces beyond the sensory deprived toggles and buttons. There is little documentation about how Seek actually worked, but that is irrelevant now given the power of currently available sensing devices to handle a similar setup. As an installation, it is the first attempt at some sort of architectonic interaction between animals and computers.

As the Architecture Machine Group writes, "If computers are to be our friends they must understand our metaphors,"[54] and Seek's abstraction of 'metaphor' to the movement of blocks perhaps provides a first step in this direction. The gerbils act naturally, on the blocks and in the space, which

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[51] Negroponte, Personal Interview.

[52] SOFTWARE Information Technology, 23

[53] Ibid.

[54] Ibid.

Fig. 2.2. Live gerbils animated the space in Seek. The computer could sense gerbil actions by measuring the displacement of the blocks. The robotic arm would ‘tidy up’ blocks based on where it sensed the gerbils wanted them (image from SOFTWARE catalog).

the computer reads in the displacement of the blocks, however the resolution and scale of the blocks constrains the gerbils' expression. The blocks are appropriate for understanding the general motions of the gerbils, but if we imagine Seek to be scaled – with, say, a giant industrial robot moving large blocks around a room – large blocks don't provide a very high resolution for human expression. Xbox Kinects now enable gestural recognition, which is a form of direct robotic vision to gain data about supposed 'metaphors', and there are also intuitive materials that can embody human expression. Increasing the resolution of interaction leads to a more comprehensive computational response. But the brilliance of Seek was using a physical object as a medium for communication. In Chapter 3, we will present a project that uses more expressive materials, such as sand or clay, to provide a similar material feedback, with a higher resolution of human expression.

Seek, in retrospect, is an essential starting point for any discussion on robotics, architecture, and human interaction. However, it is disappointing in its failure to develop to a next phase. The aforementioned Aggregate Architecture by Dierichs and Menges could extend Seek if the system could sense changes and restructure the aggregate wall appropriately, but there are few projects continuing such tectonic changes from behavioral sensing. Cedric Price, in parallel and a few decades later, was dealing with similar issues of interaction, and using technology to augment and enable these interactions. His project Generator, which will be discussed, is probably Seek's closest relative.

APPROPRIATE TECHNOLOGIES AND CALCULATED UNCERTAINTY

Cedric Price championed an attitude in the 60s and 70s towards the social effects that rearrangeable building elements and robotic systems could produce. Price was perhaps the most effective in communicating the response of technology in architecture to social requirements; as Royston Landau writes, Price was a utilitarian, and “the idea of a freedom to be useful seems to lie very close to the surface of the Cedric Price production”.[55] The freedom of the user made the appropriateness of architecture a primary concern for Price. Price did not see a building as a permanent object, but one that had a very specific shelf-life, and once it was expired, should be thrown out.[56] Furthermore, good designs must be adaptable to the stimulus of their environment. “[Planning’s] capacity to change and be changed must be accepted as a continuous rather than an intermittent process” writes Price.[57] Price’s work reflects this sentiment by capitalizing on mechanical and computational systems, as one can see in his Fun Palace and the Generator. This sentiment towards continuous change also brings into play an important distinction of time and timeliness in architecture. He writes, “[I] suggest that conscious or unconscious introduction of a time design factor in both the conception and realization of works does enhance the chances of producing a

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[55] Landau, “A Philosophy of Enabling”,10

[56] Price, Square Book, 19

[57] Ibid., 36

good design...”.[58] These concepts of time-appropriateness are essential to understanding the work of Price. His architecture takes these rationalizations quite literally, constructed of spaces that are constantly changing in an effort to “stimulate or inform, react or interact.”[59]

Fun Palace

The Fun Palace (1961), Price’s most well-known work, was never built but remains the grandfather of adaptive buildings and was influential to his later work. The structure is a simple steel frame outfitted with rotating walls and plug in rooms in order to maximize the potential uses. The space was designed for Joan Littlewood to be a working class community center in the Isle of Dogs. Conceptually, Fun Palace was designed on a principle of ‘calculated uncertainty’, which Price describes as “the creation of temporary, adaptable structures that can be altered, transformed or demolished, serving the need of the moment”.[60] The crux of his argument seems to be that design must reflect considerations for an unknown future. One of the more revealing drawings by Price of the Fun Palace is a perspective of the site in which huge steel trusses and surrounding storefronts are clearly articulated amidst heavily shaded setting (fig. 2.3). However, the center image remains untouched paper, and the trusses pop out from this void. The image allows

[58] Ibid., 46

[59] Ibid., 11

[60] “Cedric Price.” *The Telegraph.* Obituaries.

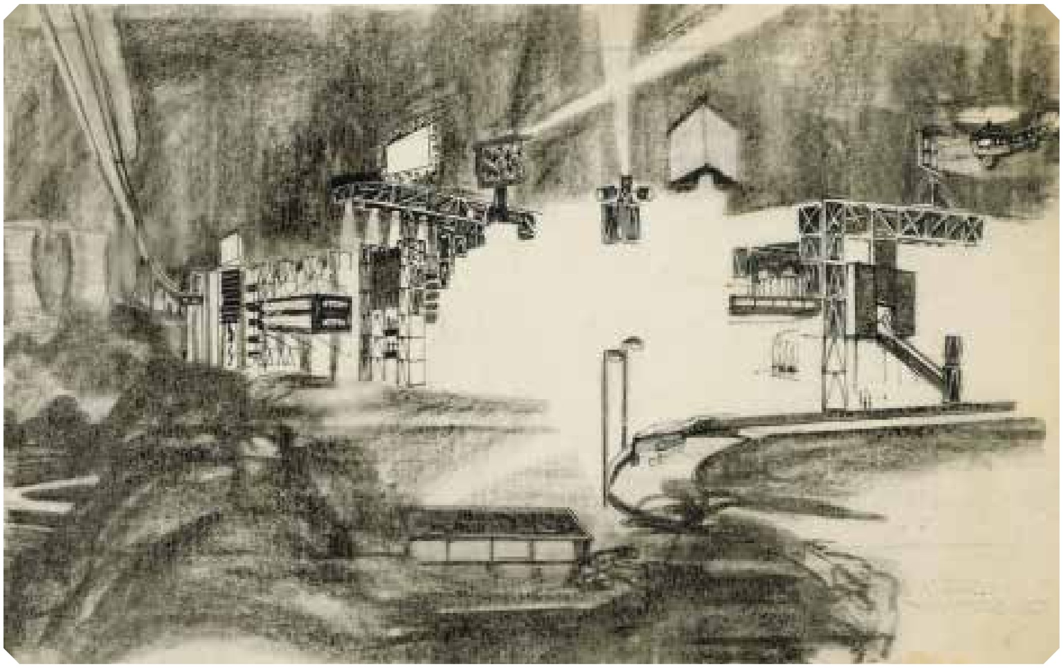

Fig. 2.3. Cedric Price's Fun Palace defined an approach of 'calculated uncertainty', in which the form of the building should be designed to change for different needs (image from Cedric Price Archive, CCA).

us to fill in the form and the use of the space between the trusses, and the contrast between the dark city setting and bright Fun Palace void conveys a design message of complete flexibility without presenting any sort of design at all. This is conceptually powerful, and made even more so when paired with the much more detailed technical drawings of the project. Unlike other visionaries of a mobile and changing architecture, such as Archigram, Price took care to isolate the necessary variables of uncertainty and produce design decisions from it. In plan (fig. 2.4), the Fun Palace reads as a free plan with two rows of supporting columns on either side of a main open space with a fifth more sparsely spaced set along the center axis. There are designated programmatic rooms, such as ‘eating’ and ‘theatre’, but the central axis is gutted to accommodate six large moving walls. Thus the building is really just a frame that can be sectioned off in various arrangements.

It also captures a certain intersection between technology and architecture. The Fun Palace is not especially high tech, but exercises an “appropriateness” of technology;[61] Price operated on the principle that “technology must be securely placed in a particular and real context from which a framework of limiting constraints could be derived”.[62] This framework, like the large steel truss frame of the Fun Palace, becomes the essential part of the design, as it is the enabler of the mechanical moving wall systems. The Fun Palace is important, then, because it expresses a working method for adaptive architecture in that the desired effect (to serve the need of the moment) is abstracted into an adaptive system (the rotating walls and plug in rooms) that is housed within a static framework (the steel truss frame).

Since the Fun Palace was never built, we can only speculate on the success of the structure. The sensibility of architecture as a tectonic skeleton and embedded with mechanical elements is noble and simple. Unlike Seek, Fun Palace is not dealing with flimsy electronic systems, but still takes on the complex problem of behaviorally responsive architecture. However, from an interfacing standpoint, Fun Palace would likely be difficult to deal with; users may compete during busy hours for different configurations, and

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[61] Landau, “A Philosophy of Enabling”, 10*

[62] Ibid., 12*

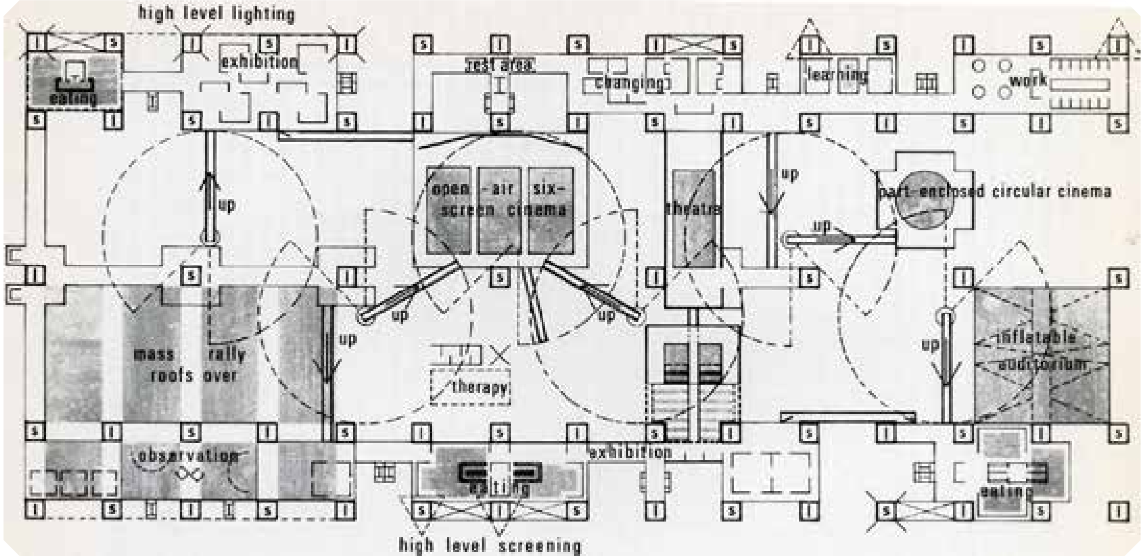

Fig. 2.4. The Fun Palace in plan shows careful consideration for program and moving parts. (image from Cedric Price Archive, CCA).

repeated visits would require repeated manual setup of the desired arrangement. The architecture cannot read user intentions, making it only adaptive and not interactive. Seek defines a conception of architecture that remembers behaviors, perhaps implying a system that, upon entry, will arrange in a way that works for you. A compromise of these two systems is the ideal, for it requires a balance of intentional human interaction in parallel with digital responsiveness. If we recall our discussion on industrial robotics, there is an absence of this kind of interactivity, in which a physical system can accommodate both real world and digital inputs. Industrial robots are just electro-mechanical systems situated in space, and how (and what) it moves in that space can produce different effects. Like the Fun Palace, the

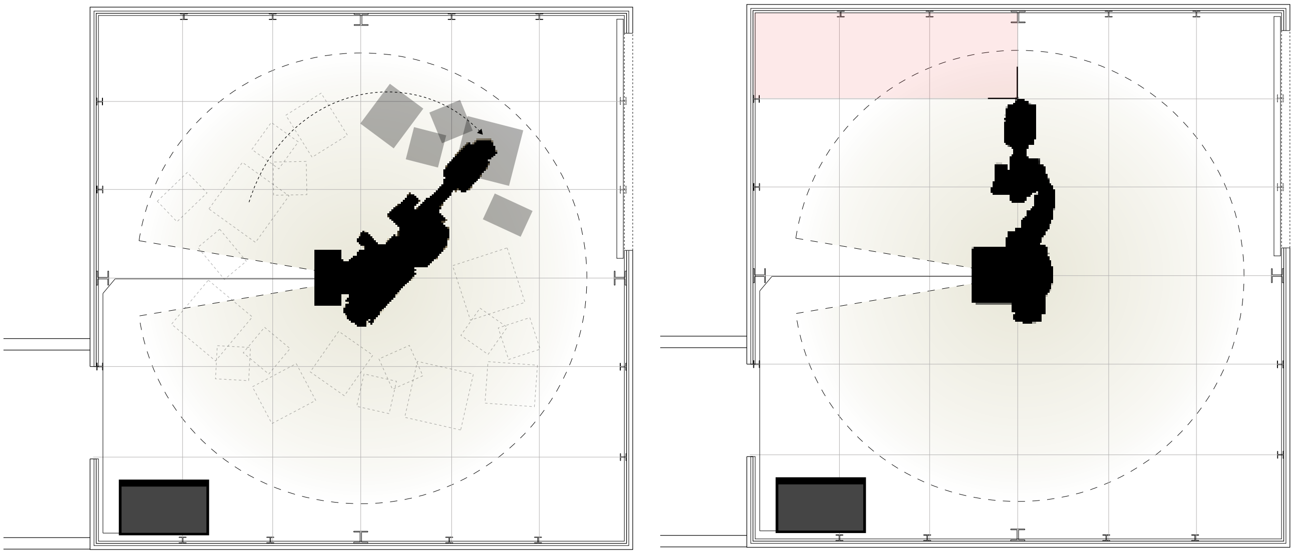

Fig. 2.5. Imagining Princeton's Labatut robot lab as a Fun Palace, the robot could redefine space by rearranging objects or delineating space with its end effector (image by Charles Avis).

robot system has the potential to activate space with its precise motion envelopes (fig. 2.5). Thus the Fun Palace presents an elegant solution to the real world input problem, but Price needed to explore another project, The Generator, to explore the digital potentials.

Generator

The Generator was a commission for the Gilman Paper Corporation in a rural location in Florida, for which the project mission was to create a secluded, intelligent environment for artists and performers.[63] The building had to accommodate various audiences and performance spaces, as well as

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[63] Ibid., 7

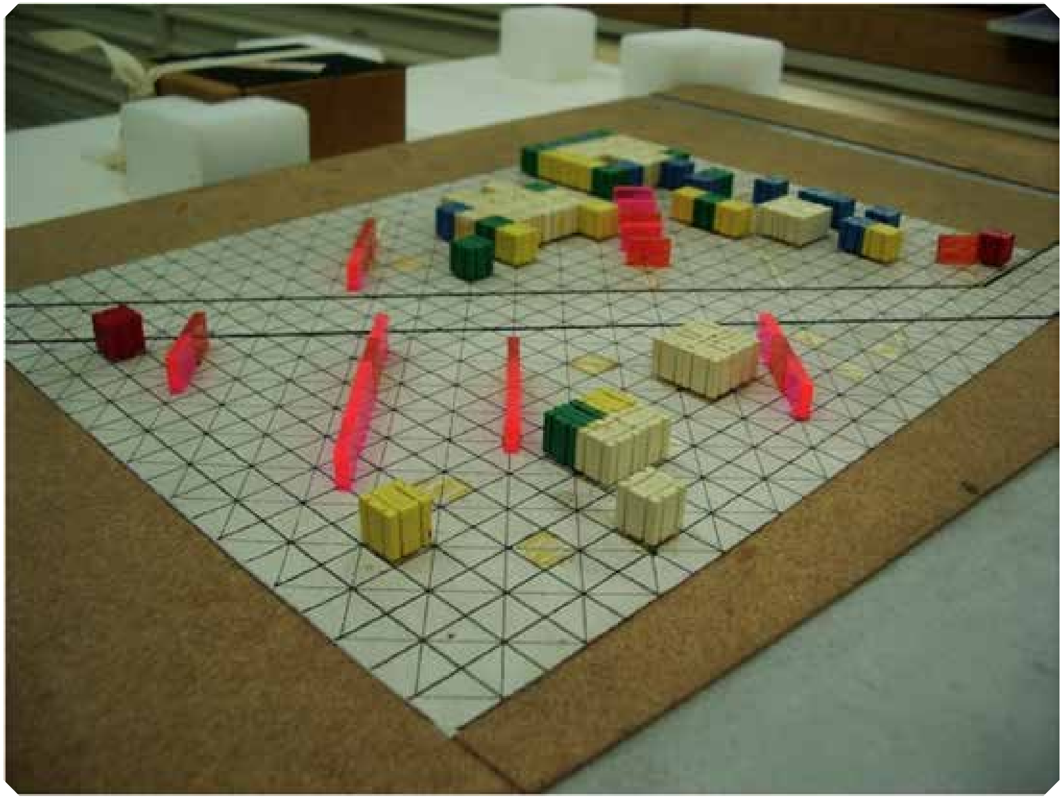

Fig. 2.6. Abstracting Generator to a grid of architectonic objects allows the computer system to recreate exactly where each object is located, and thus produce new predictive arrangements (image from Cedric Price Archive, CCA).

provide basic programs for housing, rehearsal or isolated meditation.[64] Price collaborated with the computer scientist John Frazer, who developed a central computer system to run a program that could dictate the arrangements of architectural elements. Price provided the architectural concept for the system, which was an array of one-hundred and fifty cubes, each host to a specific program, that could then be moved and arranged, and sent this

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[64] Steenson, "Cedric Price's Generator", 14.

outline to Frazer as a request for computational proposals (fig. 2.6).[65] Frazer responded with six proposals of various levels of adaptation and relationship between user and machine that became the basis for the entire system. A large crane would rearrange the cubes according to the user input. The arrangement was generated through the combination of various algorithms; one was to arrange based on a set of rules for the requirements of program or performance, another to learn from past arrangements, and provide information to the user about which arrangement may be desirable, and a final, more mischievous algorithm to alter the arrangement without any user input if the computer become "bored" over a period of time.[66] The boredom feature is of particular interest; Frazer proposes a program that includes,

> "...a boredom concept so that the site starts to make proposals about rearrangements of itself if no changes are made. The program could be heuristic and improve its own strategies for site organization on the basis of experience and feedback of user response".[67],[68]

For a building to not only respond to user and environmental feedback, but to do so in a way that is unpredictable extends further the concept put forth by Price of a 'calculated uncertainty', and is a key example of designing a non-static architectural response from data. While calculated uncertainty,

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[65] Furtado, "Cedric Prices' Generator and the Frazer's Systems Research", 58

[66] Ibid., 59

[67] Ibid., 59

[68] Frazer to Price 'Second Thoughts'

Fig. 2.7. John Frazer's prototype for Generator. The computer can read the positions of each block on the grid by polling the electrical connections between the grid, the blocks, and each block's neighbors (image from Cedric Price Archive, CCA).

in the case of the Fun Palace, pertains more to the application of design for an uncertain future, Frazer's Generator proposals begin to confront the more literal problem of how to program computers to achieve desirable user directed effects. To execute these concepts, the Frazers proposed embedding the Generator structure with electronics, turning the structure into a "giant reconfigurable array processor",[69] which is to say that the elements communicated with one another in such a way that a computer model could reconstruct a digital model of the arrangements (fig. 2.7).

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[69] Frazer, An Evolutionary Architecture, 41

This was a continuation of the work that the Frazers were doing with machine-readable models, whose goal was to develop physics models as input devices.[70] The Frazers continued this research and produced the Universal Constructor ten years later, which we shall discuss shortly. What is most striking in this approach to computationally rearranged buildings is that the human is the actuator and the system can only recommend adaptations. Thus the building becomes one giant human computer interface. Although it is difficult to evaluate how well the mechanism of moving building elements would have worked. The execution of the rearranging of elements was to be executed by a crane,[71] which had an operator (Price called him the "Factor")[72] at its helm to execute information from the Frazer computer. This process would likely be slow and tedious, and brings up questions of how literally the crane operator should and would take the computer input. Frazer conceptually confronts this problem, writing that the unimaginative use of computers could "produce an atmosphere where any utterance from the computer is regarded as having divine significance" [73]. He concludes that "the computers of our imagination are also a source of inspiration – an electronic muse" [74]. The computer then works as an augmentation device to inject measured feedback back into the physical world, the end result of which is up to

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[70] Ibid, 37.

[71] Landau, "A Philosophy of Enabling", 14

[72] Steenson, "Cedric Price's Generator", 14.

[73] Frazer, Evolutionary Architecture, 18

[74] Ibid., 18

the user. Had the Generator been built, it would have been interesting to see how much the users would have actively input arrangements. It is difficult to design a system in which computers do not produce 'divine significance' that stifles interaction. Industrial robotics, for one, completely stifle interaction.

A comparison could be the rise in popularity of personalized internet radio services, such as Pandora; Pandora operates off of a single input to generate a playlist, and users are more content to listen to the generated playlist than to spend time creating their own. There is an element of surprise and stimulation at the ordered randomness of the songs, as well as a feeling of algorithmic curation. For Generator, it seems likely that after the excitement of programming inputs wears off, the users could derive sufficient stimulation from the 'computer boredom' functionalities of the project. Further inputs would only be out of dissatisfaction with the computer-generated arrangements. A good, intelligent architectural interaction system would be the opposite, in which good arrangements stimulate productive actions. A productive action, in Generator's case, could be that the computer generates an arrangement that the user recognizes as an indicator for an action. Nicholas Negroponte writes that in the future, "mechanical partners must badger us to respond to relevant information, as defined by evolution and by context, that would otherwise be overlooked"[75], which is the extreme of what could be considered a 'productive action'. Perhaps, when the weather is nice, the Generator clears the central space and opens all the walls, which

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[75] Negroponte, The Architecture Machine, 29

indicates to the users that they should be outside. As the users populate this newly created space, they may need to move Generator parts such as walls or furniture around for different programmatic requirements, which the central computer can register and accommodate for the next time it enters this open-space mode. In this way, the users are interacting with the architecture naturally, and the interaction between user intelligence and computational intelligence is only expressed through a fluid interaction with architectural elements. As we shall see in the project proposals, intuitive mediums for humans to interact with digital information enables design processes so far left unexplored.

UNIVERSAL CONSTRUCTOR

In 1990, fourteen years after Generator, the Frazers produced the Universal Constructor, which effectively was the Generator on a model scale. The project was a system of cubes, each with its own integrated circuit, which were stacked in towers over a 12 x 12 cell checkerboard[76] (fig. 2.5). The physical system of the cubes was designed and coded to be reverse-engineered into a digital model. Each cube sent a message to its neighbors over a serial connection, and the computer processed this information into an accurate computer model of the setup. Each cube was outfitted with two LEDs for communication with the user; one flashing light indicated that the computer

[76] Ibid., 44

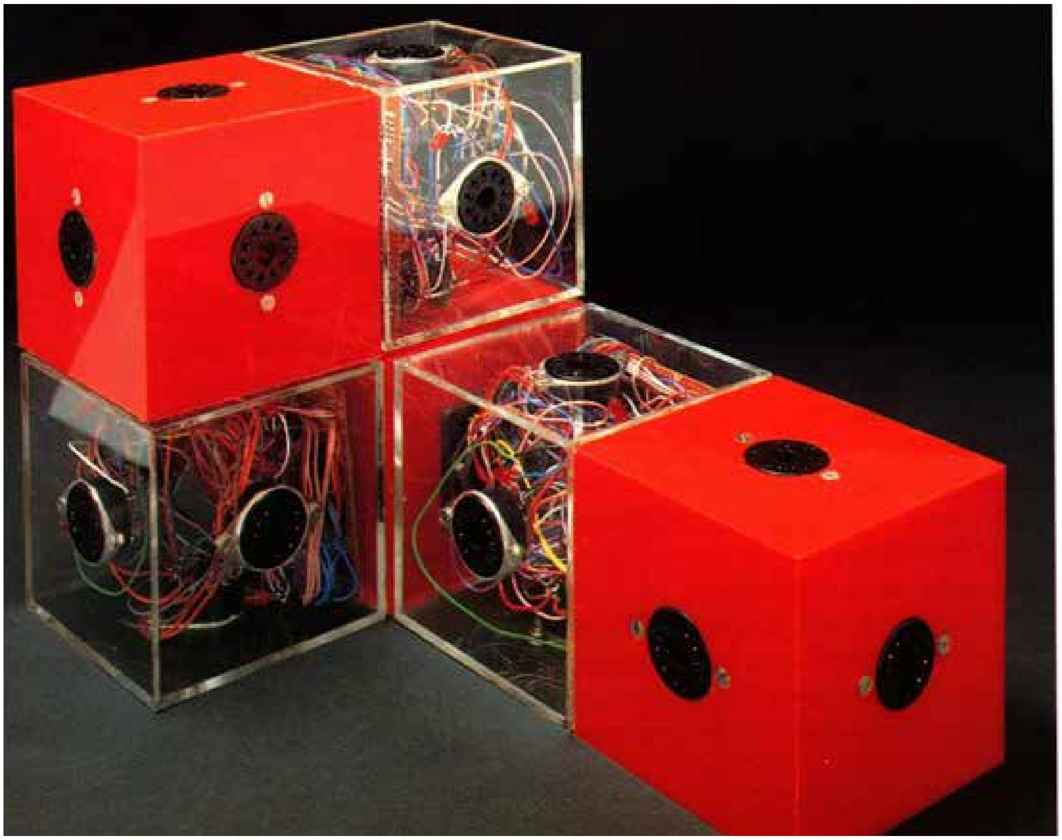

Fig. 2.8. The Frazer's Universal Constructor creates a physical three-dimensional modeling system. Each block sends information about its neighbors to a computer, which calculates the location in space of each block.

wanted the cube to be removed, and two flashing lights indicated that the computer wanted another cube added on top[77]. The user then could move and adjust the blocks, and the computer could speak to the blocks and the human actuator to optimize its rearrangement.

The Universal Constructor blocks represented an abstracted physical space – for example the high points of the stacks could be points on a contoured landscape – so the project was geared towards being a design tool as

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[77] Ibid., 45

Fig. 2.9. Universal Constructor's interface is a grid of blocks that manipulate a 3D model in the computer. The abstraction of the blocks enables the system to work, but limits the modeling resolution.

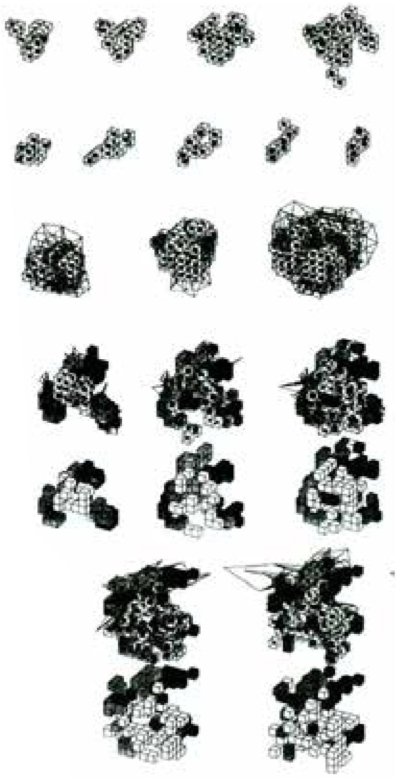

Fig. 2.10. Digital 3D models generated from the Universal Constructor.

opposed to a scalable structure. However the genealogical link between Universal Constructor and Generator is clear. Interestingly, in a comparison of the two, the same system of 'intelligent' physical space is applied in two very different architectural scenarios. Generator conceptualizes the technology as a manipulator of architectural space, whereas the Universal Constructor manipulates the architectural model. One is an adaptive architecture, and the other a design tool. This is likely due to scaling constraints, but it also indicates how similar interactive design is to an interactive architecture. Generator empowers ordinary users to become designers with the aid of the computer's suggestions. Constraints on user-inputs may differentiate a designer's input from a user's input. As an example, the difference between the digital-audio workstation (DAW) softwares GarageBand[78] and ProTools[79] is that GarageBand packages and simplifies sounds and loops to ease the assembly of a sonic composition. ProTools does not provide such packaging, and forces the user to create all these sounds themselves, thereby lifting constraints and leading to more complicated creation processes and musical intricacies. In the end, both DAWs have similar audio engines and are built similarly, but the packaging for the user determines the difference between a consumer application and professional tool. So although the Generator and Universal Constructor are cut from the same cloth, they reveal to us that there is no clear delineation between the digital tools used in design versus those that can be deployed in architecture. This observation will play an important role later on, when discussing the robotic experiments in design.

The major contribution of the Universal Constructor is the realization of an intelligent physical object, because it opens up opportunities for human and computer interactions in real space. The continued lineage of the Universal Constructor can be seen in the current work in self-assembling robots, such as the M-Blocks from MIT,[80] however the work in affording de-

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[78] ® Apple, Inc.

[79] © Avid Technologies, Inc.

[80] Romanishin, “M-Blocks”.

signers and users the ability to manipulate the digital world from the physical space has been neglected. In the contemporary discourse in computation, the field of architecture has for the most part dropped the idea of human as actuator, favoring the industrial robots and other digital fabrication devices as actors upon material. The M-Blocks as well are not designed to take user input. However with easier access to robust and (relatively) cheap sensing tools, such as the Xbox Kinect and Arduino boards, it is easier to fill the digital world with real world data. Collecting data on a user's interactions with a material can be achieved through the computational analysis of a scanned point cloud without constructing the 500 integrated circuits in Universal Constructor.

CONTEMPORARY MANIFESTATION

The conceptual elements that Price, Negroponte, and Frazer contributed focus on the different ways that both humans and computers can contribute to an architecture, but this interactivity covers a lot of ground and must be carefully defined in order to be fit within the contemporary discourse. Price was part of a movement interested in Cybernetics, which defines a circular feedback loop between environment and machine, but as opposed to trying to reconstruct the argument from the 1960s, we must redefine more specifically in contemporary terms what circular feedback can be considered interactive. Michael Fox, in his book Interactive Architecture,

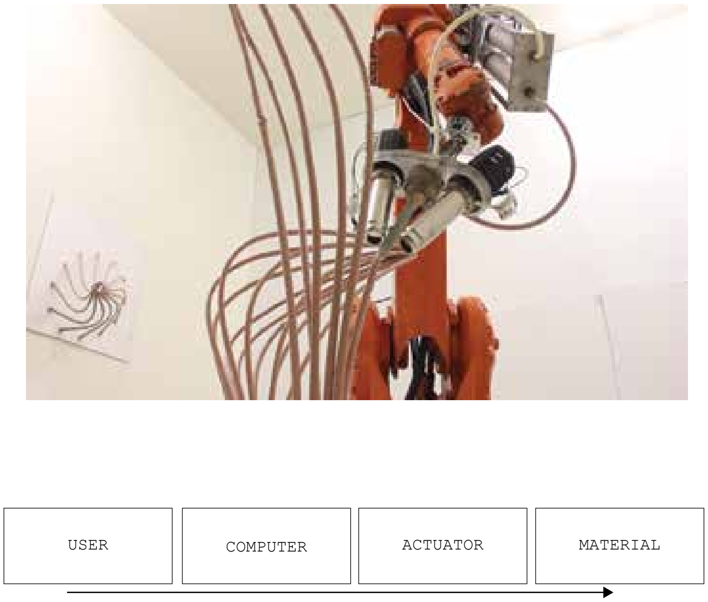

Fig. 2.11.1. Digital fabrication has a linear sequence of interaction, with no feedback. (image: Mataerial, Jokic)

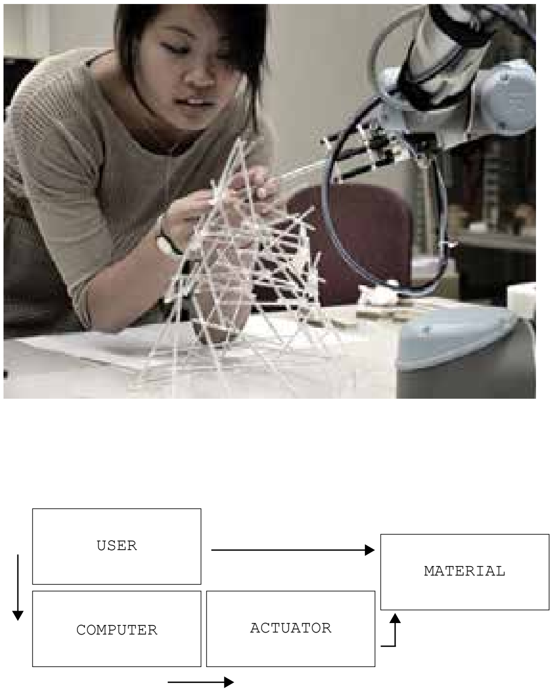

Fig. 2.11.2. In some interactive attempts, the human and robot work in parallel, but with a determined result. (image: Gramazio & Kohler © ETH)

writes that interaction with architecture should allow people to ‘participate’, rather than simply ‘use’.[81] This implies not just a reactionary architecture that responds to user input, but that in some way the response affects the participant. The Universal Constructor achieved this effect through the visual cues offered by the embedded LEDs and the Generator affected spatial arrangements. In both cases, the central computer offers some interpretation of the user input, which helps break the paradigm of simple input-output models. The interpretation can be optimization, computer boredom, or crowd-sourcing – anything digitally computed that the participant can then

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[81] Fox, Interactive Architecture, 13

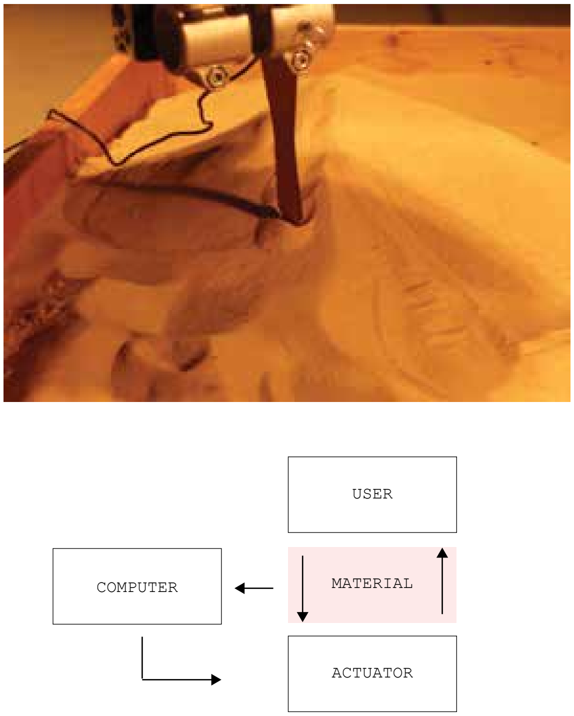

Fig. 2.11.3. A viable feedback loop for robotic interaction could capitalize on external materials. (image: SandCastle, Avis)

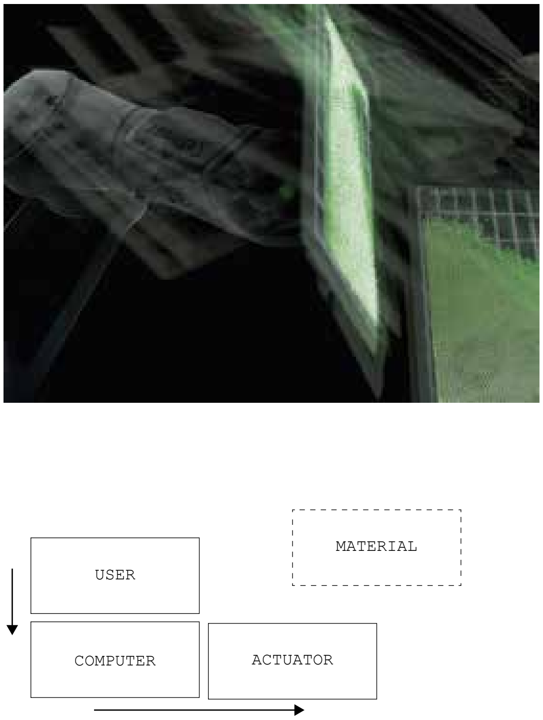

Fig. 2.11.4. Some robot projects don't concentrate on interacting with material at all, using the robot as an animator. (image: Projection Mapping on Moving Objects, Kruysman Proto)

respond to with aesthetic or experiential purpose. Considering the industrial robot as the digital instrument of choice, to develop interactive experiences with the robot requires a sharper focus on interpretive programming, as well as interfaces to enable evolving contributions from the participants. These interfaces must be abstractions that are intuitive and find a balance between direct programming and full automation.

There is already some considerable work that focuses on this real world interaction between humans and computers. Free-D is a project by Amit Zoran and Joe Paradiso from the MIT Media Lab which is a hand held milling device with built in motors to assist with milling accuracy.[82] The user can set different tolerances, and the hand held mill acts as a tool for hand craft with integrated digital information. The tool can recognize a barrier around the desired 3D model, and if the mill bit will penetrate that barrier, the mill will retract and not penetrate the material in a way that would compromise the target model. Because the device is handheld and under full human control, the concept of digital suggestion in fabrication as opposed to a fully automated setup is quite novel. The device appears to work quite robustly, and still relies on a digital model in order to execute its function. It is an interesting take on the confluence of gestural input by humans and a calculated response. Many gestural projects, such as Frog Design's E-Room[83] or AlloPlastic Architecture by Behnaz Farahi[84] read body motions to actuate a structure, but Free-D connects directly with the user, making gesture not a method of control, but keeping it as an intuitive series of actions on an object. Interactive feedback must consider a level of intuition for the user, and since programming robots is not generally an intuitive act for architects or designers, interactive experiences can't try to teach a new language of communication, but instead augment already natural and developed avenues of communication. Intuitive feedback requires the computer and robot to understand human input through a feedback loop (fig. 2.9).

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[82] Zoran, "FreeD – A Freehand Digital Sculpting Tool".

[83] "Room for a Revolution: Frog E-Room".

[84] Farahi, "AlloPlastic Architecture", 129

In the context of these historical precedents, industrial robots can be extended as design tools by enabling more robust participation. SCI-Arc, Bot & Dolly, and ROB Technologies all show interest in the development of more agile and user-friendly software to interface with the robots. The current extent of interactivity with this software is in the ability to quickly program robotic movements, observe the result in live motion or animated simulation, and then adjusted parameters accordingly. The interactive loop exists to some extent in the ability to quasi-rapidly prototype and adjust movements, but this is limited by the graphic interface. Outside of the architectural paradigm, some industrial robots can take haptic input from users, such as Baxter from Rethink Robotics.[85] People can teach Baxter movements by moving its arms to desired locations, and Baxter can then replicate these motions repeatedly. This has benefits of lowering costs of operation, because engineers and programmers are not required to operate the robot,[86] and thus reduces many barriers to entry that haunt other industrial robots. However, to abstract this concept away from a specific robotic system, less computational and more physical interfaces could have massive benefits for the quality of interaction between the physical and the digital. This is, ultimately, the effect that Frazer, Negroponte and Price were striving for.

The projects discussed in this chapter had ambitions on scales ranging from the installation to the interface to the full-blown intelligent build-

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[85] "Baxter: A Unique Robot with Unique Features." Rethink Robotics.

[86] Ibid.

ing. Each presented a conception of architecture and architectural design that adapts to changing inputs, and in turn affects the actions of the user. They are architecture as a human-computer interface. However, as we shall see, this ideal quickly runs up on the limits of what is technically feasible in the short term with industrial robots. Thus we isolate variables of interactivity, such as tangible interfaces and human-readable motions, and focus the following project proposals on the development of these variables. The end goal is for an appropriation of the industrial robot that expressively performs digital information, as a new and expressive way of realizing the industrial robot as an architectural mediator between human and computer.

CHAPTER 3

SIMULATIONS AND SAND CASTLES

In this chapter, we will propose three projects that aim to turn architectural mediums like material and space into mediators between humans and digital models.

Thus far, we have discussed a survey of projects within architecture and other creative disciplines that explore the industrial robot as a tool for making and producing. What we can conclude from this discussion is that the two distinct realms of projects using industrial robots – construction and representation – do not fully explore how design with robots can be more interactive. To be interactive, the design process must be more continuous, and veer away from the tendency to do one-off fabrication projects. A more continuous process means that the robot as a tool should be employed at different phases that precede the production of a product, such as simulations of spatial experiences, and interactions through material. The historical lineage of Cedric Price, Nicholas Negroponte, and John Frazer shows an interest in interactive and performative architecture enabled by computing technology, and their human-centric approach to robotic, computational and architectural interactions is achievable to some degree with industrial robots. The work of Price, Negroponte and Frazer now finds its closest living relative in the Tangible Media Group from the MIT Media Lab, run by Hiroshi Ishii. The Tangible Media Group operates within the vision set out in 1997 of 'Tangible Bits', which proposes a "design challenge [as] a seamless extension of the physical affordances of [objects] into the digital domain".[87] This is to say that Tangible User Interfaces (TUI) are a trajectory of research concentrating on physical manifestations of digital output and input. The Universal Constructor is one of the first advances into this realm,[88] whereas the Generator gives little indication of containing a digital input interface beyond an ordinary graphic user interface (GUI). However, what the Generator did conceptualize that has remained unrealized in TUI developments is response to the digital input that has consequences on the architectural scale.

What would an architectural human computer interface look like? Tangible User Interfaces face a few fundamental limitations that robotic practices have the potential to extend. In 2012, the Tangible Media Lab announced a new vision statement, coining the term 'Radical Atoms', which responds to the observation that "TUIs are limited by the rigidity of 'atoms' in comparison with the fluidity of 'bits'".[89] The new vision for Radical Atoms is "a computationally transformable and reconfigurable material that is bidirectionally coupled with an underlying digital model...so that dynamic changes of physical form can be reflected in digital states in real time, and vice versa".[90] This bi-directionality of physical inputs and outputs perfectly describes the concept of interactivity with architectural robotics that deserves further exploring.

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[87] Ishii , "Tangible Bits: Beyond Pixels", xv

[88] Ibid., xix

[89] From Tangible Media Website: http://tangible.media.mit.edu/vision/

[90] Ibid.

By synthesizing both ‘Tangible Bits’ and ‘Radical Atoms’, the historical precedents in architecture that we have thus discussed, and the discussion of architectural robotics, we arrive at a place in the discipline that seeks a user interactivity between the digital and physical, but an interactivity that is carefully defined and mediated through architectural responses. It enables the robotic motion to enter a design-centric space, as opposed to its primary use as the creator of objects and images. Two avenues of architectural feedback we will explore are how the robot can expressive communicate in space and through material.

How can working with an industrial robot become intuitive for architects? What sort of real-world feedback on digital designs is useful for architects? If a robot could collaborate on model making, then generate spaces that respond to those models (or vice-versa), it would become a tool that could assist in prototyping each phase of the design project. Industrial robotics offers a tool through which to realize architecture from the scale of the Universal Constructor all the way to the scale of the Generator. Easily available tools such as the Xbox Kinect and parametric modeling software like Grasshopper and Processing can be interfaced with the industrial robot to enable a certain amount of interactivity. The following three research projects are models that try to utilize the expressive, performative qualities of the industrial robot along the novel trajectory of architectural interactivity.

SANDCASTLE

SandCastle is a proposition for material modeling as the medium for physical-digital interaction. Using a simple scanning procedure and digital analysis of the scan, human interaction with a material can trigger robotic interventions onto the same material. This proposal borrows conceptually from the Tangible Media Groups SandScape and John Frazer's Universal Constructor, and extends our discussion of Zurich-style projects that are concerned with the construction and procedural methods of robotic manipulation of material.

SandScape, developed at MIT, is part of a research vector within the Tangible Media Group on 'Continuous TUIs'[91], which is an effort to break from the limitations of the discrete block objects as seen in previous projects like Urban Planning Workbench (fig 3.2).[92] The setup was a square container of sand with an overheard projector and 3D scanner aimed downward at the sand from above. The scanner interpreted the topology of the sand, and the projector projected live data onto the sand based on various landscape analysis algorithms (fig. 3.1). A user could rearrange and sculpt the sand, and the system would update its projected information to accommodate the new design. The system provides dynamic feedback between material and computational analysis in a way that leaves interpretation and actuation of

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[91] Ishii et al, "Bringing Clay and Sand into Digital Design", 287

[92] Ishii et al, "Augmented Urban Planning Workbench".

Fig. 3.1. SandScape from the Tangible Media Group at MIT. Projectors display GIS data on a scanned clay landscape (photo from Ishii *et al*, 2004)

the system to the user, however it is limited by the sculptural qualities of the sand and the inherent inaccuracies of the human as sculptor. Optimization data can only be interpreted, and the system provides little direction as to how the designer might use the projected information to optimize the landscape model. It is an analysis tool that enables user input and interaction, yet lacks a scalable and robust method for turning data into physical design. Thus SandScape provides a powerful model for digital interaction. Combining its representational power with the actuation of robotics, however, allows for real-time realization of the landscape optimizations.

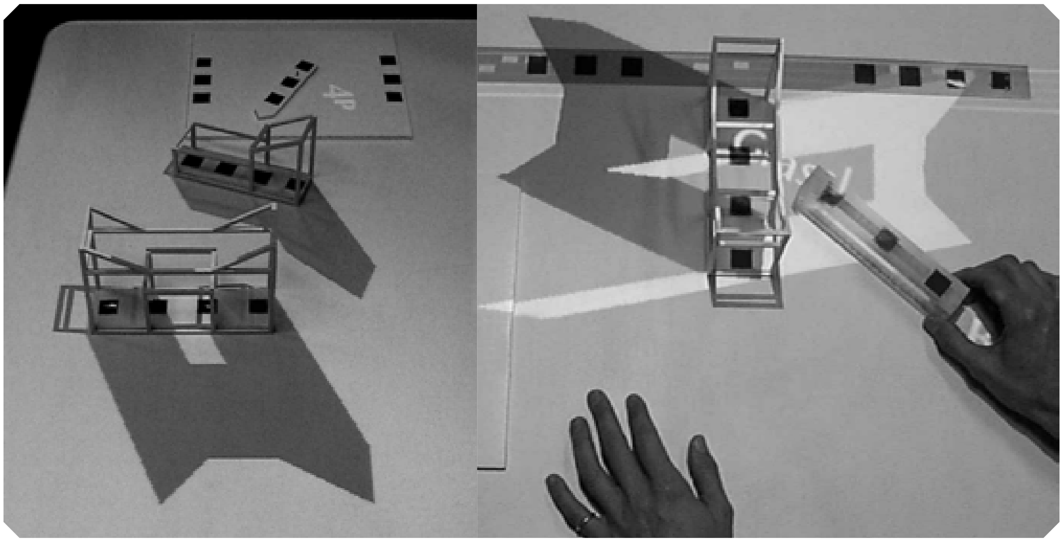

Fig. 3.2. The Urban Planning Workbench by John Underkoffler, in which scanned objects generate shading and wind analyses that are projected on that table. As with SandScape, the digital information is purely represenational. SandCastle proposes robotic intervention into a tangible setup like this. (photo from Underkoffler *et al,* 1999).

SandCastle extends SandScape through the physical manifestation of the quantitative landscape analysis data. SandCastle enables the physical restructuring of the material to inform design decisions. Optimization becomes an integral part to the process of making. Thus, a human and robot can trade off working on the same object, and each actor's actions influence the other.

Software

SandCastle is set up by coordinating scanning technology, software analysis, and robotic actuation. Due to the feedback loop from scan to actuation, human intervention is worked into the system, much in the same way that SandScape updates its visuals in real time as the sand is sculpted.

Fig. 3.3. The setup for SandCastle. The robot moves to this scan position, determines where it needs to go, then manipulates the sand with the wooden end-effector (photo by Charles Avis).

If an architectural model, or a sand castle, is built or placed in a landscape of sand, the robot sees the structure, knows its topology, and can sculpt the landscape or manipulate the model based on chosen digital design parameters.

The software component for the SandCastle provided a challenge for a system that could be integrated with architectural analyses as well as work fluidly with sensing technologies like the Xbox Kinect. SandCastle is written in the Processing[93] language, and implements the libraries SimpleOpenNI[94] to interface with the Kinect, and ToxicLibs[95] to execute mesh analysis and vector transformations. The pseudo code for the Processing implementation can be seen in figure 3.4. The Processing code works in series with the program running on the IRB 7600 robot, meaning that it only executes the scan operation once the robot code is in the correct position, and then the robot will not move again until Processing sends the calculated robot positions over a serial connection.

There are three primary algorithms that work in series within the Processing sketch: the first is a background subtraction algorithm, which enables the Kinect to read changes made in the sandbox as discrete objects. Two successive scans will result in a mesh of the differences between the two scans, so if the sandbox is scanned before and after an object is placed (or a sand castle is made), then the placed object will register as a mesh. Once

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[93] Fry and Reas, Processing v2.1.

[94] Rheiner, SimpleOpenNI v1.96.

[95] Schmidt, Toxiclibs, v0020.

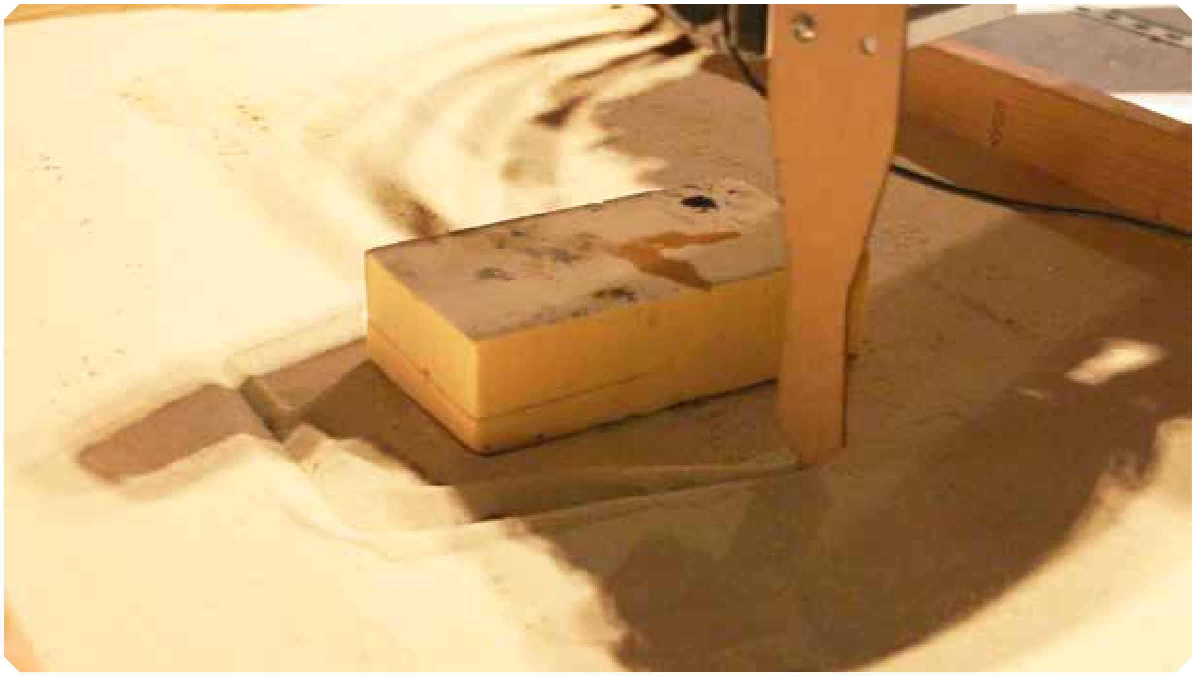

Fig. 3.5. A placed object, or even sculpted sand, will register as a human intervention, and the robot can act accordingly. Above is an example of the 'moat' algorithm that traces the outline of the sensed object (photo by Charles Avis).

the mesh is obtained, it is much easier to analyze it to produce optimized or analytical robotic actions. Since the background mesh – or the first scan – can be saved in a variable, it is also possible to record more continuous changes in order to make user feedback more fluid. For this implementation, scans are taken incrementally by the choice of the user. Once the user has finished sculpting the sand landscape, he or she calls for the scan, which then triggers the robotic action.

Once the difference mesh is obtained, the second set of key algorithms in the code is to analyze that mesh, and reduce it to parts that can then become robot movements. These algorithms make up the design and aesthetic of the system, for they are where landscape and object analyses are written. MIT's SandScape presents a number of landscape analysis algorithms that are useful for design, such as view-shed analysis, shadowing and solar radiation, optimal road placement, and water drainage,[96] yet designing these algorithms to not only be displayed to the designer, but to initiate robotic manipulation requires another level of algorithmic design.

The first algorithm implemented was not based on an optimization, but rather an interest in the robot's ability to tend or contribute to a fluid building process. Every sand castle needs a moat, so the first algorithm projects the vertices of the object mesh onto the XY plane of the sand, finds the two-dimensional convex hull, and offsets this outline of the 'castle', thus producing a tool path of the outline of the castle. The robot then uses this tool path to dig a moat (fig. 3.5). This same concept could generate a Japanese zen garden raking path around placed rocks, and represents a model system for user interactions. Further development could concentrate on making the development of algorithms more open-source for further research at the Princeton Labatut lab, allowing students to customize analysis procedures for use with this setup.

The third and final step in the software is to translate the result of the analysis algorithm into a usable robot code. Princeton's ABB IRB 7600 is a six-axis robot and runs off of the RAPID programming language

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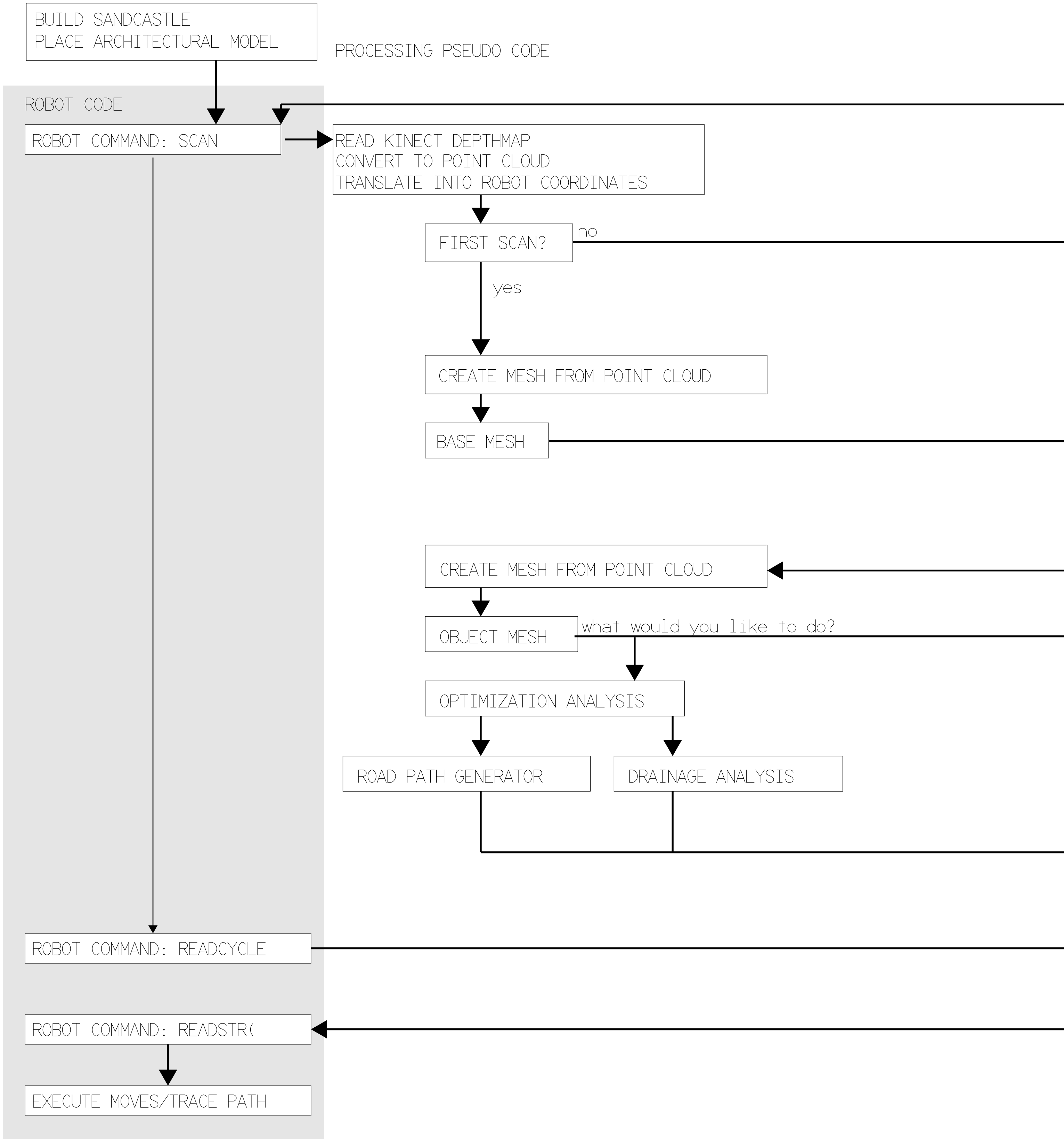
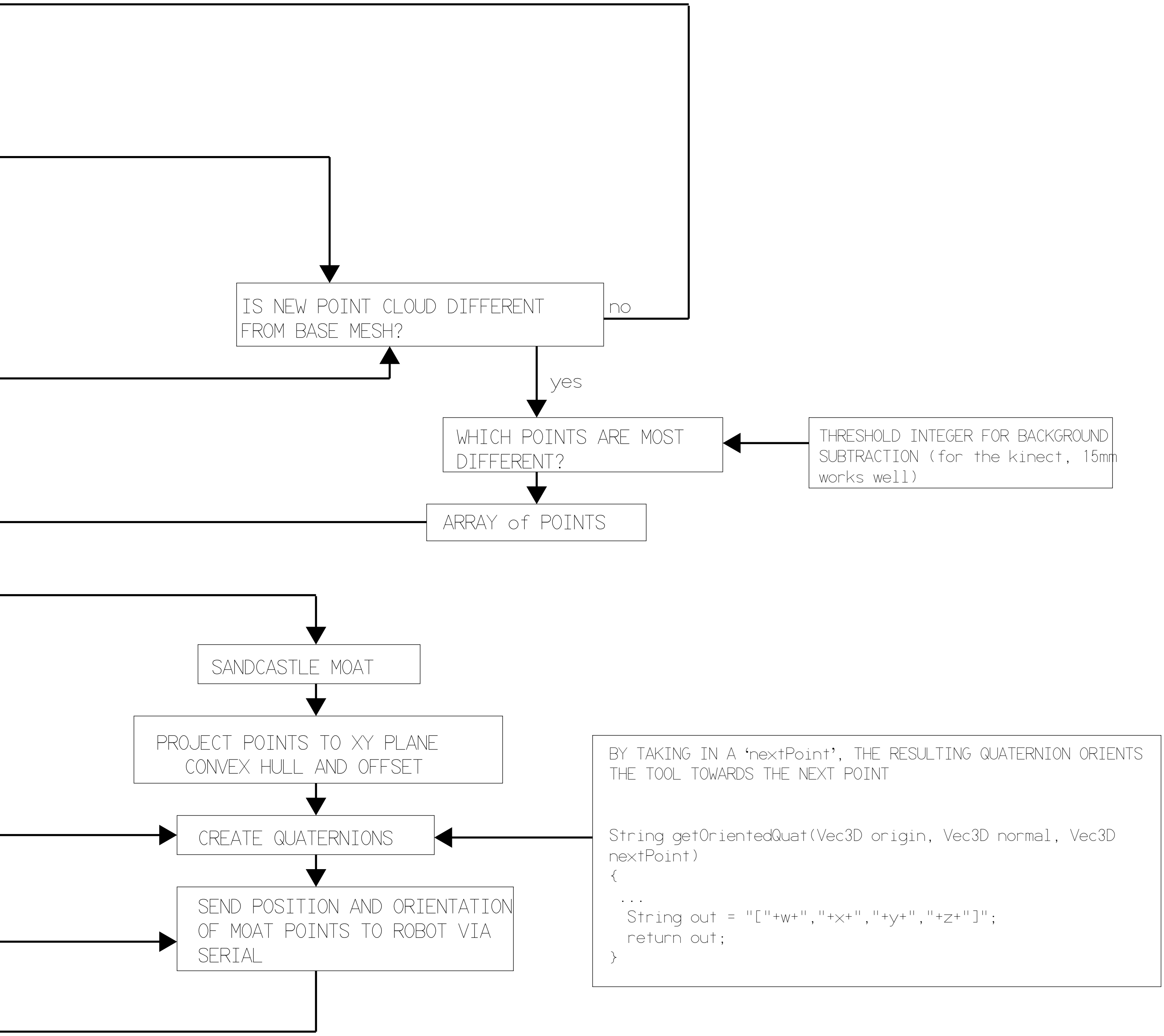
[96] Ishii et al, "Bringing Clay and Sand into Digital Design", 294-295


BUILD SANDCASTLE
PLACE ARCHITECTURAL MODEL
PROCESSING PSEUDO CODE
ROBOT CODE
ROBOT COMMAND: SCAN
READ KINECT DEPTHMAP
CONVERT TO POINT CLOUD
TRANSLATE INTO ROBOT COORDINATES
FIRST SCAN?
no
yes
CREATE MESH FROM POINT CLOUD
BASE MESH
CREATE MESH FROM POINT CLOUD
OBJECT MESH
what would you like to do?
OPTIMIZATION ANALYSIS
ROAD PATH GENERATOR
DRAINAGE ANALYSIS
ROBOT COMMAND: READCYCLE
ROBOT COMMAND: READSTR(
EXECUTE MOVES/TRACE PATH



BY TAKING IN A ‘nextPoint’, THE RESULTING QUATERNION ORIENTS THE TOOL TOWARDS THE NEXT POINT

```
String getOrientedQuat(Vec3D origin, Vec3D normal, Vec3D
nextPoint)
{
 ...
  String out = "["+w+","+x+","+y+","+z+"]";
  return out;
}
```

Fig. 3.4. Pseudo code for the SandCastle system.

with the ABB S4C+ operating system. In its simplest form the robot can execute a move given a position in space and an orientation (described by the variable *robtarget*), a speed variable, zone data, and tool data (which in our case could be the Kinect or the shovel). It can also be specified to move linearly through space via the command MoveL (on a straight line from one point to another), or through a joint interpolation via the command MoveJ (each joint moves to its new position at the specified speed). It is also possible to set each joint value manually via a command MoveAbsJ. A sample command that will execute a linear move from the robot's current position in space (measured in millimeters) to a target position and orientation is shown below:

	robtarget					
Command	pos	orient	configuration and exterior axis	speeddata	zonedata	tooldata
`MoveL`	`[[500, 500, 500]`	`,[0, 0, -1, 0]`	`, cf, ex]`	`, v500`	`, z10`	`, xtion;`
Move linearly through space	To a position in space 500mm in the positive x, y, and z directions	Orient point downwards along the negative z-axis	Ignore these	Max linear speed of 500 mm/s	Begin turning or slowing within 10mm of target point	Use the position and orientation offset of the 'kinect' tool

These details are important for our discussion to help demystify what types of constraints robotic projects must operate within. It is interesting that in the end, we are only controlling three variables: what position it moves to, which way it points when it gets there, and how fast it moves there. Thus to create something truly complex, the complexity often must come from outside of the robotic system. Gramazio & Kohler believe in procedural design through programming and code,[97] and Bot & Dolly and SCI-Arc work with the complexity of synchronization of systems.[98] The complexity in an interactive setup as we are working with here can be achieved from both the computational interpretation of the scan data, as mentioned previously, as well as the timely communication with the robot's computer. The Processing platform for SandCastle calculates the *pos* and *orient* data from the output of the analysis algorithm and loads these values over serial into an array of *robtargets* in the RAPID code.

Upon a signal from the robot indicating it is ready to receive its next points, the scan and analysis process runs and fills an array of *robtargets*. This allows one scanning instance to initiate complex robotic movement. An incremental scan-then-move approach is chosen at first in order to simplify the timing synchronization between the scan interpretation and subsequent serial communication. For the user, this means that once the sand is sculpted in such a way that is satisfactory, the user may initiate the robotic se-

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[97] Gramazio & Kohler, Digital Materiality, 10

[98] Proto, Personal Interview.

quence, which will vary in time and length based on the complexity of the analysis movement. It would be interesting to play with this time variable, and find the sweet spot in response time by the robot. Too long of a response time reduces interactivity, as it begins to resemble more the slower feedback processes that rely on digital interfaces. Continuous interactivity is not feasible due to the safety constraints of occupying the same space as the moving robot. Safety is further compromised in any scenario that is taking sensory feedback, especially from the Kinect, which is often prone to glitches that may result in dangerous robot moves. Safety mechanisms are written into the Processing and RAPID code to prevent the robot from reaching outside of a set bounding box, but this would not mitigate dangers involved in continuous feedback. A safer setup would potentially be the line of Universal Robots that occupy the desks of a classroom at the DFAB at the ETH,[99] but the IRB 7600 still provides a powerful platform to test these feedback communications.

There are, to be sure, much more complicated and sophisticated protocols for communication between robot and computer than a simple serial connection, and it would be exciting to see how such robust, instantaneous communication systems could expand the possibilities of this interactive setup.

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[99] ETH has 6 Universal Robots. “flexible, silent, low cost arms” http://www.universal-robots.com/

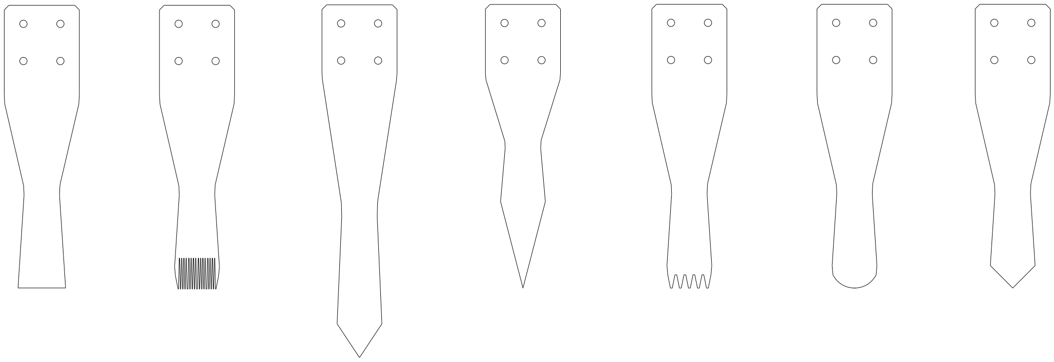

Fig. 3.6. Designed end effectors for sand manipulation.

Materials

A sand box placed within the reach envelope of the robot becomes the work object for this test. The most desirable sand is green sand or modeling sand, which more easily holds its shape when manipulated. For this instance, we used stock all-purpose sand, similar to play sand. An ASUS Xtion (similar to the Xbox Kinect) was mounted to the end effector of the robot, along with a tool for manipulation. The tool was kept simple, as the movements generated through the scanning feedback could be outfitted with the necessary digital intricacies. Rakes, shovels, and flat stamping objects are all possible end effecting tools (fig. 3.6). The double sided end-effector was programmed into the robot as two preset tools so that it would be possible to alternate between scanning positions with the Xtion and manipulating actions with the installed tool.

Fig. 3.7.1. Model custom landscape

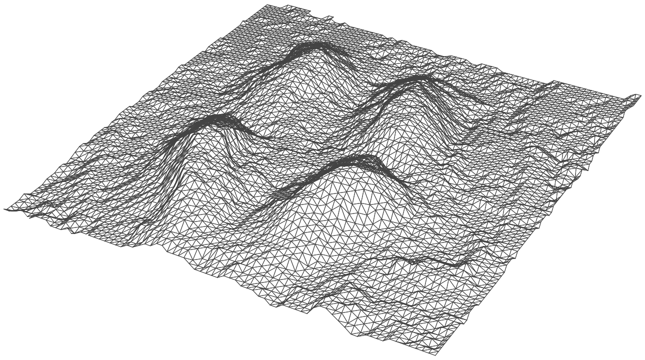

Fig. 3.7.2. Digital scan of landscape.

Results

It was expected that this setup would open possibilities for sophisticated digital optimization and modeling to influence the act of making. When there is the expectation of robotic intervention on the finer, digitally calculated details, then the workspace can become more efficient as a space for generating rapid design prototypes for landscape designs, urban planning massing, and other designs involving ground manipulation. Learning from the Price-ian approach to technology, the experiment is also intended to be stimulating and playful, and the effect of robotic actuation triggered indirectly plays into the fascination with robotic movement.

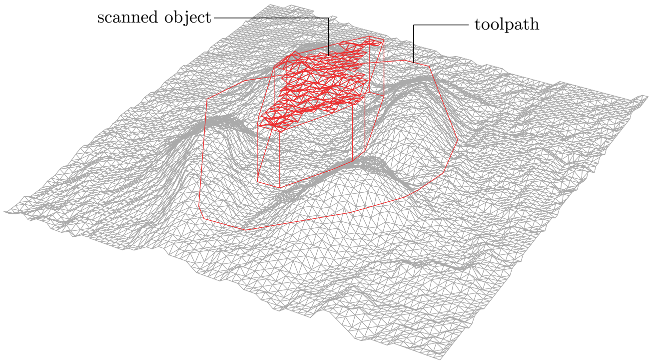

Fig. 3.7.3. Addition of object in landscape generates offset toolpath.

Fig. 3.7.4. Robot drives to dig around the placed object

The first tests of the moat-drawing algorithm worked very cleanly and robustly, tracing patterns around the objects or sand mounds that I built up in the space(fig. 3.5, 3.7). This algorithm was at a set height, so it would plow through the sand irrespective to the sand's topology. To do more of a surface trace, the second test was to project the convex hull line to the topology of the sand, while keeping the tool normal to the sand's surface. This tracing motion was much cleaner and expressive, and allowed a raking tool to leave clean combing patterns on the damp sand. With each scan and raking motion, I could then move a foam block object around on the sand, and it would continually draw this expressive convex hull around the block. When done repeatedly, the system could become a 3D sand drawing tool, with the foam block object as the physical interface.

Fig. 3.8.1. Model custom landscape and place marker to indicate starting point of road

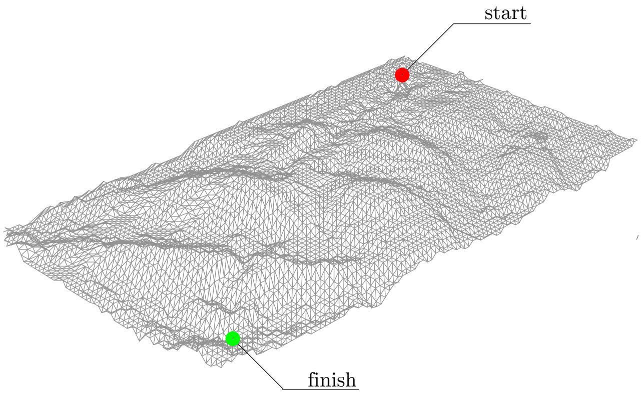

Fig. 3.8.2. Digital scan of modeled sand, identifying start and end points

To delve deeper into the analysis functions and break from the foam block as the object of interaction, two different types of analysis algorithms were then tested: the first being a drainage analysis of a landscape, and the second a path of shallowest ascent (i.e. most gradual road path) across the modeled landscape (fig. 3.8). The first calculates the path of steepest descent from a given point. The second road analysis iteratively finds the shallowest path across a landscape. The robot then can trace either one of these calculated paths into the sand to represent the optimal path for a drainage chute or for the placement of a commuter path. For each, the quaternion for the robot was generated by looking at the next point that it had to move to and orienting the tool to be normal to that path.

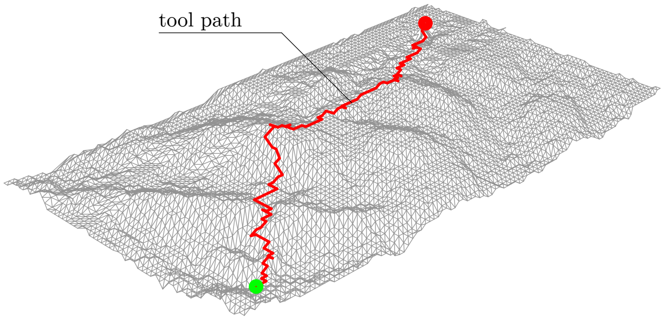

Fig. 3.8.3. Road optimization on scanned model

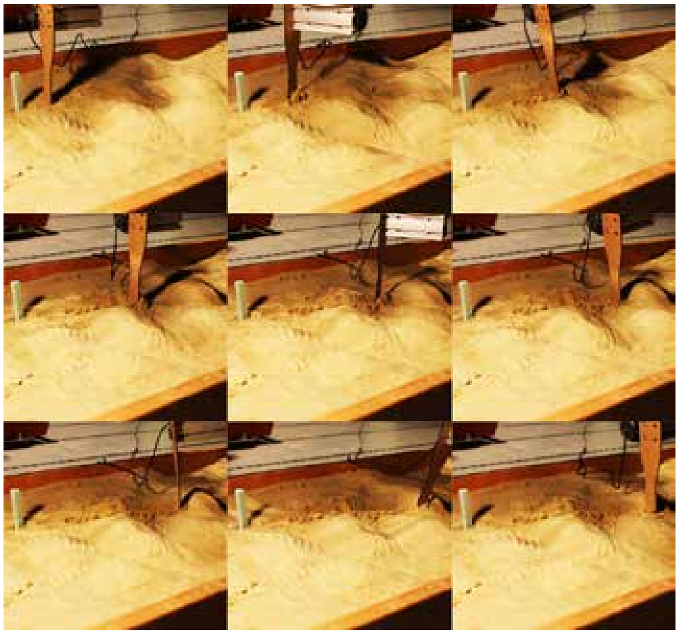

Fig. 3.8.4. Robotic trace on physical model of road path.

The drainage function found the highest point on the sand, and looked at each surrounding point from the 3D point scan to find the its lowest neighbor. By following its lowest neighbor, it would generate a path until it reached a local minimum. The system worked as it was designed: a user-constructed landscape would generate a tool path that appeared to accurately descend down the steepest part of the mountain(fig. 3.9). Since the analysis is confined to the grid of scanned points, the movement is relatively jerky, and implementing a look-ahead in the analysis would smooth out the path considerably. Since the quaternion is looking one point ahead, the robot very expressively traces out the drainage line. Each change in steepness and direction is exaggerated by the axes of the robot reorienting around

Fig. 3.9. The traced path resulting from the drainage analysis in SandCastle. (photo by Charles Avis)

the rake tool-tip (fig. 3.10). This was an unexpected result that was quite fascinating, as the optimization path is not only drawn into the model, but performed by the robot.

This observation was even more powerful with the optimized road path. Since the road algorithm looks for shallower grades, the reorientation of the robot is slightly more subtle, but watching it stretch backwards when climbing up a hill and lean forwards as it descends was the most informative physical manifestation of the movement. Because the tool tip did not cleanly plow through the sand, the path left on the sand is more representational than precise. However, the pivoting and changing direction of the tool is readable in the sand, and leaves a quite beautiful pattern. Unexpectedly,

Fig. 3.10. The robot expressively tracing the calculated drainage line from the top of the mound (photo by Charles Avis)

the constraint of the scan grid was generative of road patterns, and further exploration of the pattern-generating abilities of this system would be interesting.

It is quite fascinating to sculpt a landscape knowing that the robot will act upon it. Simply due to the placement of the camera I was using to document, I found that I needed to edit my sculpted landscape numerous times to ensure that the drainage or road algorithm would run down the camera's side of the mountain. Using the computer visualization as an expectation of robotic movement was one thing, but knowing that the robot would act upon the model forced extra attention to the shape of the landscape. Further development of truly iterative versions of this experi-

Fig. 3.11. The foam block is a tangible indicator for the computer to set the starting point of the road path simulation (photo by Charles Avis).

ment would help solidify its interactive potentials. For example, building a landscape, then generating a drainage analysis, then designing volumetric massings on the landscape outside of the flood zones, then running a path optimization through the massings would be a fluid design process that would perhaps better show the power of interactive work flow. However, what the finished experiments did reveal was that the robotic movement does indeed provide more information than just a visual representation can. The three-dimensional elevation changes, as well as expressive reorientations confirm that robotic actuation on the design space brings new elements that digital simulation can not so clearly express.

The problems that arose in these experiments can be attributed to

Fig. 3.12. The traced path resulting from the drainage analysis in SandCastle. (photo by Charles Avis)

some problems with the serial packets that the computer running the processing code sent to the robot controller, as well as the connection and visibility of the Xtion. The Xtion does not register points when the sun is out, as the Labatut lab has four glass walls that reflect light so the experiments needed to be held in the evening. The problems with serial generally arose if the program was terminated (often due to a Null Pointer error) in the middle of the loop that sent the information to the controller. This meant that the buffer did not clear properly. If, however, the Xtion was scanning properly and the serial connection was synced, the system worked quite robustly, without ever sending the robot unreachable coordinates. Without a proper inverse kinematics model to work from, the moat and contour drawing functions require a check to make sure that axis six of the robot does not reach its maximum rotation, as the tracing functions require the end effector to rotate in a full circle while tracing the profiles. Once implemented, scanning and moving and modeling could be executed repeatedly.

Much like Antoni Gaudi's hanging models, the SandCastle system enables a designer to work through an analog medium, while at the same time embedding in that medium essential information. The robotic imprints in the sand are digitally calculated and informed by topological information, and also potentially generative in the design process for the formation of road patterns and material deposits (fig. 3.11). Gaudi's models directly translated to the structural measurements, and the SandCastle models trigger environmental measurements, and is able to adapt to this required information. It is worth noting that there is a nostalgia to working through an analog medium that today's digital architects may not desire, or know how to use. However, even in the development of SandCastle itself, being able to express ideas in the sand through drawing, building, or pointing is powerful. SandCastle is a design tool, but with the development of drones – which have considerable range and precision – and bigger, better robots, it is possible to imagine a scaled version, in which drones sculpt the landscape on a 1:1 scale, or a robot tends to a garden with an awareness of the plants and objects in it (much like Seek tended to the gerbils' environment). There is not a definitive line between SandCastle as a design tool and as a fluid actuator on the real world.

SPACETRACING

Building upon the same conceptions of robotic communication and control as SandCastle, SpaceTracing is a proposition for simulated architectural space as the medium for physical-digital interaction. Space can be perceived and experienced, and the programmable movements of the industrial robot offer an opportunity to prototype spatial arrangements in a way that has not before been explored. Space is explored here as a result of kinematic motion, using physics simulations and parametric models to discover ways that the robot can trace volumes or the path of objects as a way of giving feedback to the user. Control mechanisms developed and theorized encourage the rapid prototyping of space. This spatial interaction derives from our discussion of the Los Angeles-style cinematic approach, as it is unconcerned with the creation of an object, and instead exploits the performative power of the robot.

At its simplest, this interaction type was tested by attaching wooden dowels to define a corner of a box (fig. 3.13). The space that Princeton's robot is housed in is a large cube with plan dimensions of 24' x 24'. The cube's walls are comprised entirely of 4'x 8' glass panels, held together by steel mullions. The mullions create a distinctive grid across each wall, spaced 4' apart horizontally and 8' apart vertically. To exploit this existing grid, the wooden dowels defining a corner are moved by the robot to measured points in space that coincide with perceived intersections of the grid (fig. 3.14). The dowels

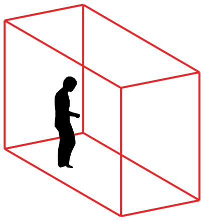

Fig. 3.14.1. 3D digital model of box

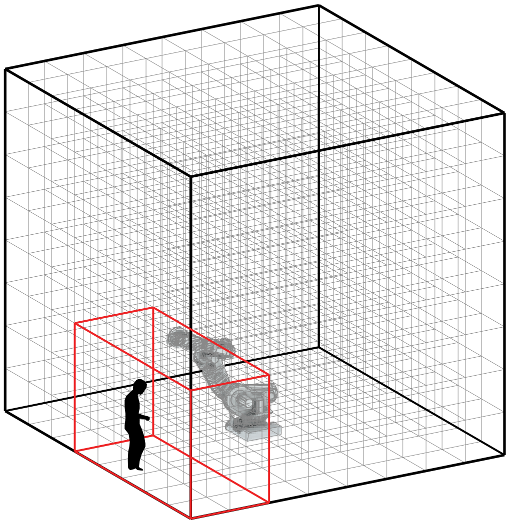

Fig. 3.14.2. Digital simulation of box in robot space

work in tandem with white mullions to form perceived rectilinear volumes (fig. 3.13). Since the reach envelope of the robot is limited, it is not possible to reach each virtual intersection of the mullion grid, however, varying heights and rough spatial delineations were perceivable. The mullion grid is essential in this type of setup, and provides a potentially useful constraint in its standard construction dimensions of 4’ x 8’. Moving to static points that line up rectilinear volumes is only a starting point to other potential strategies for prototyping architectural space. Evaluating space is subjective, and adding further perceptive information may increase the effectiveness of spatial feedback. Ground and wall projection would augment the space further. An effective design space for future research would be a Processing sketch

Fig. 3.14.3. Robot delineates model box in real space

Fig. 3.14.4. User evaluates box space in real dimensions

that simulates the space around the robot, and breaks it up into voxels as in fig. 3.14.2. This sketch could coordinate a wall projection, floor projection, and the spatial orientation of the robot. The user could then draw boxes in space and the robot and projections would sync to those coordinates in the real world. The interactivity in this setup is not as refined or complex as in SandCastle, but if the system can respond quickly to the new parameters set by the user, then the user can quickly go from model to real space, using the subjective spatial feedback as new input into the digital model.

The advantage of this model to the emerging research in augmented reality headsets is the potential for spatial prototyping to include physical objects that people could interact with. If the robot can manipulate large

Fig. 3.13. The robot lines up with the mullions in Labatut to simulate a corner of a box for SpaceTracing

wooden walls or foam blocks to help delineate the roofs, walls, or tables, then the user could have a seat at the table, or reach out and touch the walls to give the simulation a tangible quality. The wooden dowel end-effector may not be the most effective for the SpaceTracing concept either. Elastic bands connected between the mullions and the end-effector, or curtains pulled back and forth, might provide more sensational spatial experiences. To extend the interactive nature of the simulation, of further interest would be to parse a digital architecture model, through which a user could move in the digital model, and the environment of that room would be constructed in real time with a form of SpaceTracing. As a design tool, SpaceTracing has clear prototyping benefits, but it also has potential as an embedded object in a contemporary Fun House. The ABB IRB 7600 is not the best tool as an embedded object, but as the articulated arms get safer and more robust, it is not too far fetched to imagine a building that actuates different spatial arrangements in accordance with requirements in real-time. Greg Lynn's SuperAeroRoboSpatial studio approaches this future from a more top-down perspective, and developing SpaceTracing as a design tool could begin to realize a more fluid conception of architectural space.

SIMFURNITURE

To further explore the use of robotic motion as a definer of space, and mediator between physical and digital animations, another test was setup to simulate the action of a rocking chair. Instead of translating material changes into robot commands, as was the goal of SandCastle, the rocking chair model translates digital simulation into robot movements. There is a disconnect in the Zurich style between the architectural product and the means of its production. The industrial robot provides an enabling platform for not only construction, but the simulation of the building's performance. By combining physical simulation with the building process into a single work

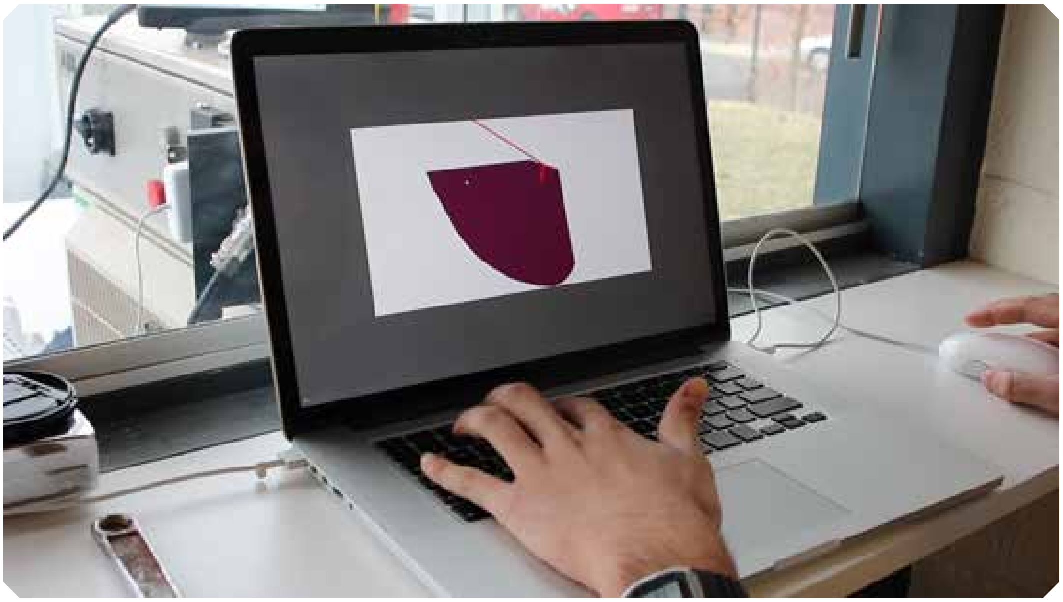

Fig. 3.15. A physics simulation of a rocking chair profile can produce a motion envelope to be instantly prototyped.

flow, an interface for architectural design is created that extends beyond the interface of the computer.

For the rocking chair prototype, a design space was setup in the Processing environment using the Fisica library by Ricard Marxer,[100] to allow a user to draw the profile of a rocking chair and run that form through a physics simulation. Working only in two dimensions, the profile curve drawn by the user is rigged to a given flat 'seat' to create the chair profile as a rigid body (fig. 3.15). The physics simulator then runs an approximation of the movement of the chair, and a custom function tracks the movement of the 'seat' and generates commands for the robot based on its translation

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[100] Marxer, Fisica, v0.1.14.

Fig. 3.16. The robot executes fluid, exaggerated movements generated by the physics simulation. In this particular simulation, it is clear that the rocking chair would have tossed a user off the chair to the left.

and rotation throughout the simulation. The two-dimensional space of the Processing sketch, is then mapped to a work object in the robot's coordinate system so that the robot's movements mimic the orientation of the processing sketch (fig. 3.16). The complementary physical setup is once again kept simple; a board mimicking the dimensions of the rocking chair seat is secured coming out of axis six.

This setup is a first step towards rapid simulation in real space. The spatial moves offer important feedback to the designer. However if a rocking chair were really to be tested for its comfort and rocking smoothness, it would require real time control of robotic movements that adapt to the human's shifting weight. Furthermore, for the setup to be truly interactive

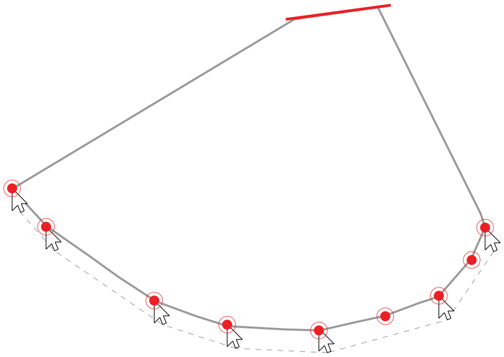

Fig. 3.17.1. Digital drawing of chair profile

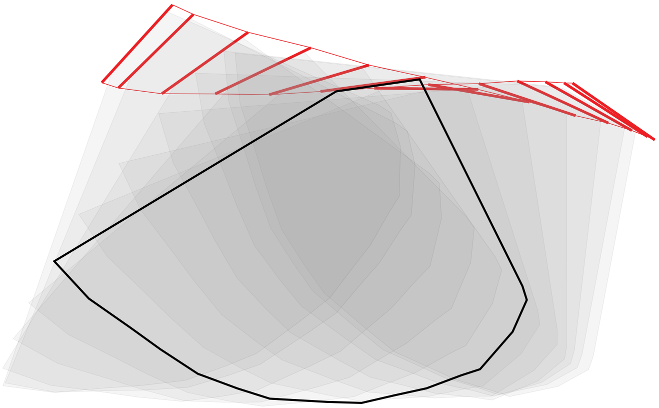

Fig. 3.17.2. Digital simulation chair motion

in the physical space, strategies for creating a feedback loop in real space must be developed. The ideal setup would be to embed force sensors in the seat held by the robot, and live human input would make the seat react according to the real forces interpreted through the physics model. Safety concerns render such a setup implausible, as the physics model is prone to glitches that send the chair flying off into space, as well as uncertainties with real-time serial messaging. The IRB 7600 is not the ideal tool for such a simulated setup, but specialized simulation tools can be expensive and limiting,[101] and the industrial robot's generic-ness allows for a wide variety of simulation scenarios.

Building real-time control protocols is essential to integrating any

[101] Ferrari's F1 Simulator cost about $6,000,000. http://blog.axisofoversteer.com/2012/01/6-million-dollar-spider-ferrari-f1.html

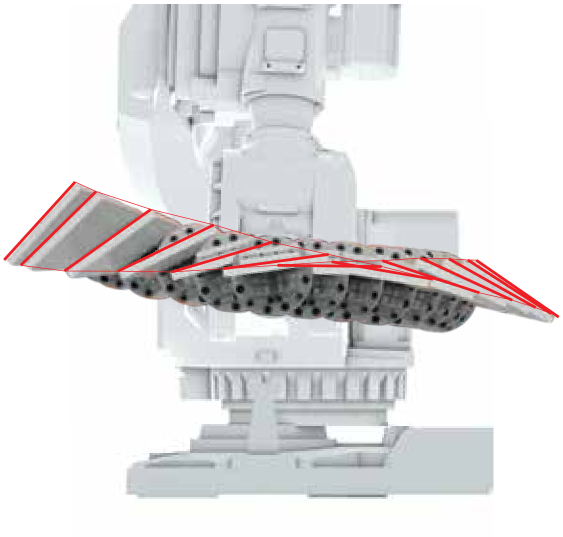

Fig. 3.17.3. Robot traces seat motion in real space

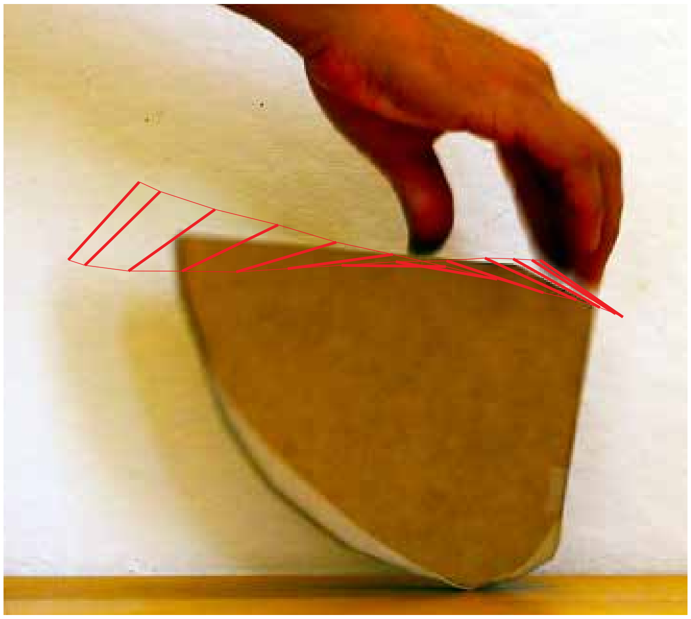

Fig. 3.17.4. Confirmation of motion with physical prototpye

adaptivity and interactivity into the simulation, so a series of tests were setup to begin examining interactive spaces. The pseudo code for the ideal functionality can be seen on the following spread. We expected to be able to implement a version of live control that would allow for the agitation of the physics model in the Processing sketch, and for its effects to manifest in robotic motion simultaneously. A first test was setup to stream robtargets over serial from a Processing sketch that gave the user control over the orientation of the sixth axis and movement along the global X-axis. A lag of about one second occurred in this setup between the initiation of a movement in Processing and the response by the robot. This is likely due to a look-ahead in the robot's computer, and makes it difficult – if not impossible – to have the simulation respond in real-time. Furthermore, once the robot has begun

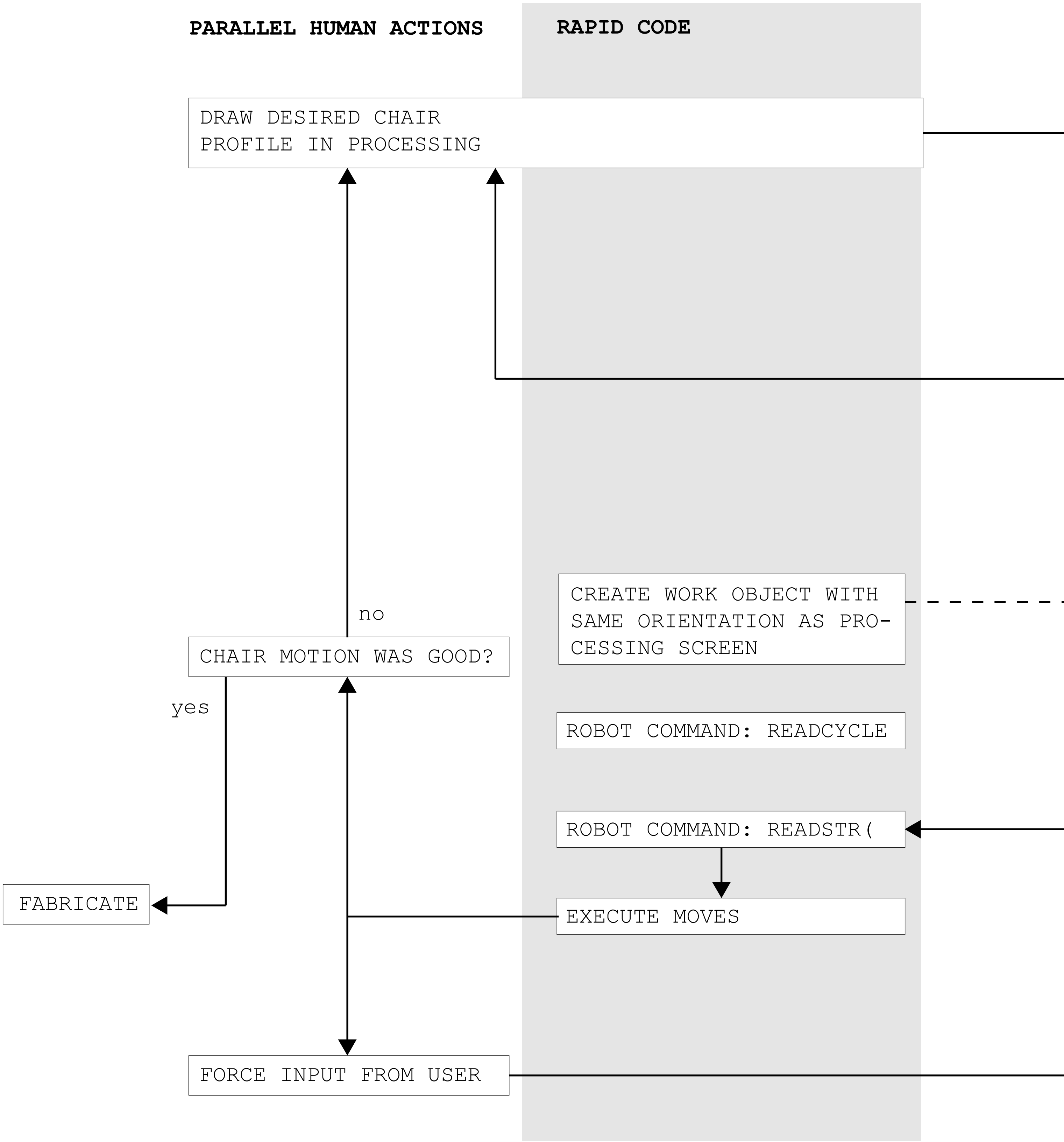

Fig. 3.18. Pseudo Code for SimFurniture

PROCESSING PSEUDO CODE

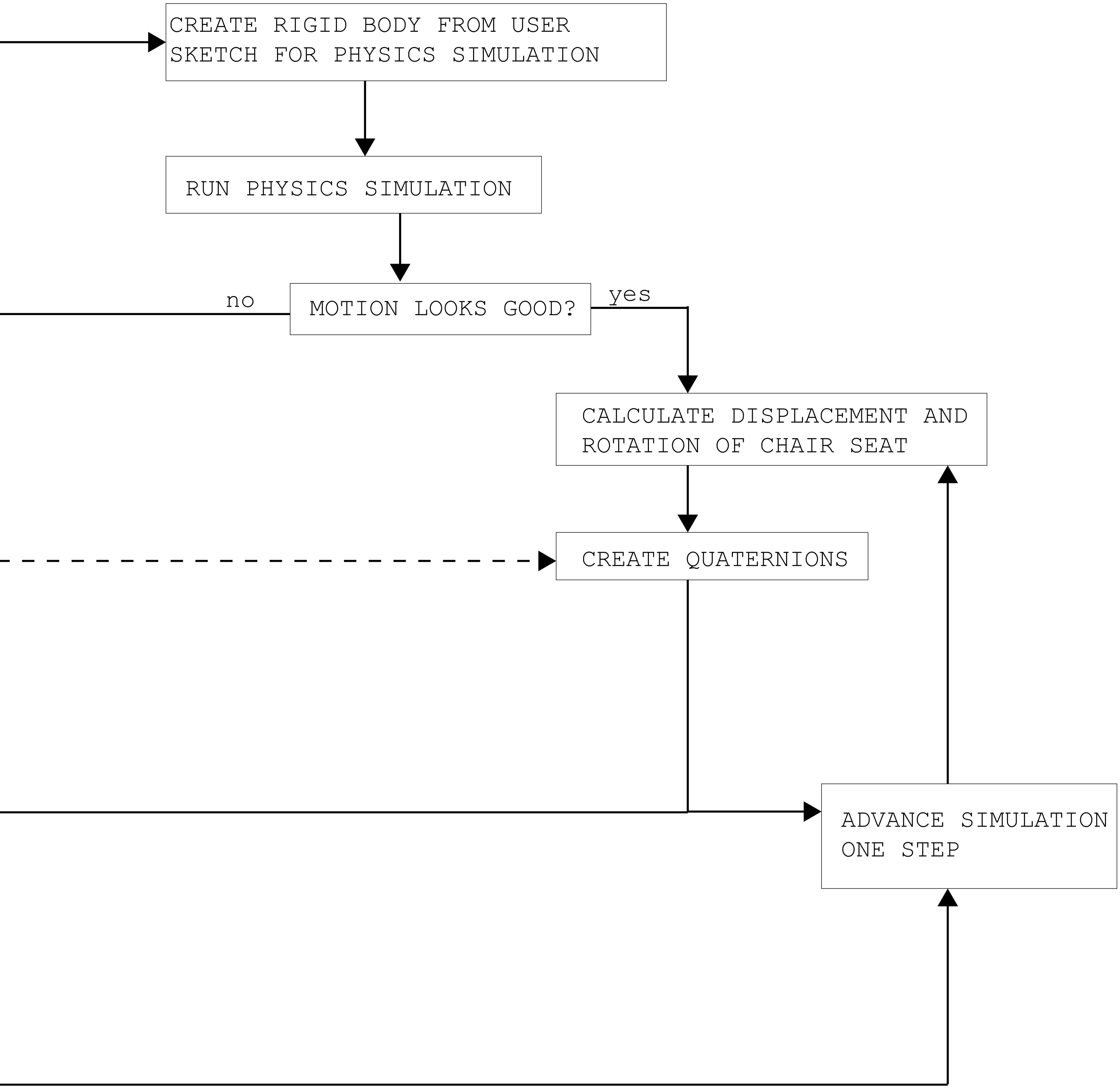

Fig. 3.19. Testing real-time control of chair movements in Labatut with Ryan Johns. A lag between digital simulation movement and robotic movement made live control difficult due to jerky movements and imprecise response. (photo by Charlie Avis).

executing a movement command, it must reach the end of that move before being able to adjust to its new position. This could potentially be solved through multi-tasking,[102] in which an interrupt command[103] will update the

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[102] Multi-tasking is a functionality on the ABB S4C, S4C+, and IRC5 in which a background program can communicate with the primary program by manipulating global variables

[103] Possible interrupt commands are SearchL and CorrCon. SearchL, when prompted by an i/o input, will interrupt the current movement if sent a new coordinate, and CorrCon allows for rapid updating of path offsets given sensory input.

move coordinates, but it is as yet unclear whether these adjustments will execute in any semblance of real-time.

The lag may not be such an issue if the nature of the simulation is slow. The action of a garage door or the revolving walls of Price's Fun House are simple to spatially prototype, as direct user input inflicts a change in the space. Any automated setup could be simulated in such a way. The more empathic motions in design, however, like the subtle recline of a desk chair, or resistance of opening a door are more difficult, and likely impossible with industrial robotics. The giant ABB robot, designed originally for automobile manufacturing, does not have the necessary safety and programming protocols for such simulation, but by taking on some abstractions, we tried to get close to prototyping these spatial and physical envelopes. Returning to the rocking chair model, we extracted the robotic move commands from the seat as described previously, and implemented a multi-tasking protocol to give the user control of the scrubbing speed through the simulation. This failed because it is not possible to call movement commands in a background multitask. Theoretically, an interrupt command to reverse the direction of the program along with the real-time scrubbing provides a solution to real-time reactions to movement. The next step is to implement an interrupt command, or look into the CorrCon functionality to adjust movements in real-time.

One conclusion from this project is that the industrial robot is not perfectly generic, and it finds its limits with many of these interactive instances. For precision and motion it is useful and accurate, but to get more real-time feedback and interact safely with the environment may require different tools. Under the constraints of the Labatut lab at Princeton, the robot is still the most useful tool without building custom robotic setups. Whereas a custom Stewart platform may be the most appropriate tool for the experiential prototyping discussed here, the installed robot has fewer barriers to entry and can achieve to some effect the desired movements.

SPECULATION

The proposed solutions to an increased interactivity with industrial robots represent interventions into the design process that aim to augment rather than produce. Each project is a design system for Princeton's IRB 7600, complete with prototypical software interfaced through Processing, that attempts to reduce friction for early-stage physical prototyping. Two speculations are fruitful to evaluate the impact of these systems, one along its development as a more robust design tool, and secondly how these experiments could scale.

Industrial robots are still quite rare in architecture[104], but if they can become accessible to architects as a powerful design tool, then their number will continue to grow. Even if the six-axis industrial robot never quite catches on, there will be some other digitally-controlled actuator to take its

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[104] According to Robots In Architecture, there are 45 places in the world (Although Princeton has not been counted) http://www.robotsinarchitecture.org/map-of-robots-in-architecture

place (such as drones or something as-yet unknown). In order to improve interactivity with programmable manipulators like the industrial robot, we need to focus first on hurdles of safety. Even with sophisticated control technologies, the strength and speed of these industrial arms is too intimidating and risky to get too comfortable around. 'Soft' robotics like those being developed at Otherlab and Festo are an option, but sacrifice strength and precision. Assuming that technology is developed to guarantee the safety of these robots[105], then small scale interactive setups, like SandCastle, can become more fluid and real time. We discussed in chapter 1 that most robotics projects thus far have determined outcomes, and this is likely due to the fact that industrial robots are designed to produce determined products without intervention. As we reduce the barriers to human intervention and collaboration during robotic production through safer robots and flexible software, then the robots can become fully integrated objects in design spaces and architectural spaces. For example, for the designs from SuperAeroRoboSpatial by Greg Lynn's Suprastudio[106] to be realized, absolute confidence in the mechanisms of motion would be required for such large movements of building parts. An elevator solves this issue by internalizing the mechanisms and interfacing with the user through a rigid, static box. For large scale ambitions like Lynn's suggestion of robotically-moved buildings parts internalizing robotics may be the solution, but then its performative and reactive

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[105] Perhaps someone will invent the SawStop (http://www.sawstop.com/why-sawstop/the-technology) for industrial robots.

[106] "Greg Lynn Suprastudio".

power is lost. Soft robotics provide a much more interesting suggestion, as they can occupy the same space as humans and interface with them directly. The SandCastle concept here discussed would benefit greatly from this advancement, as robot and human could collaborate on material not series but in parallel.

We discussed in the SimFurniture experiment a desire for real-time interaction as well. In a rocking chair simulation, force sensors could read the distribution of weight transfer, and the physics model could adapt accordingly, thus driving the robot reactively. Embedding objects with sensors to drive robotic responses like this is an area that requires further development. Imagine a space in which each element has force sensors, and the design process became a matter of pushing on walls that would robotically move to the desired location. Currently, digital fabrication and this proposed design simulation are still reliant on CAD software and digital programming, but as robots bring articulated digital motion into the real world, and objects are able to read detailed information through sensors, there is a possibility for architectural design to occur more in physical space. Even in the most basic of client-architect meetings, the architect could benefit from quickly orienting the robot to the height of a counter or bench so that the client could approve of each dimension from a haptic experience.

Considering robots as interactive tools also opens possibilities for robots as elements in architecture. In the same way that SpaceTracing used the grid of mullions to help delineate space, what the robotic arm can do depends on the space around it. If a robot is to move elements of a room around based on programmed arrangements, then the robot would need to be situated in the room so that it had access to all the objects. This brings up questions of how prevalent robotics should be in architecture. The same questions exists in the design stages. To what extent do people want to interact with robots? Ease of operation is a clear obstacle, as is safety and usefulness. The potential of their usefulness is clear: SandCastle can produce optimized forms and landscapes, SpaceTracing could catch potential mistakes of dimension and arrangement, and SimFurniture allows one to test a design before spending any effort or money on its fabrication. There is an economic argument, as the robot can perform these versatile tasks, is cheaper than a new car, and would likely pay itself off if used regularly.

As interactive robotics leaves the architectural design space to become architectural objects, not much of this argument changes, as any action that the robot is doing could be reduced to a simple new decision of design. Inherent in an interactive system is some level of design, and there is potential for a future architecture that is the design of systems – embedded with robotics – in which the architect relinquishes control over many of the finer details. This is a Cedric Price-ian approach to a future architecture, in which architecture becomes an enabler for the user. For now, however, designers need to continue creating systems and interactions with robots, and only through iterations can the designer understand what is necessary and what is possible.

CONCLUSION

The industrial robot has not reached its full potential as a tool for architecture. We have presented an overview of important projects involving the industrial robot, and have discussed how it is an object for making, but to realize its full potential, robotics must incorporate more continuous human interaction. The current discourse focuses primarily on determined robotic results, in which robots execute linear processes in order to produce a product. These contemporary projects also reveal that industrial robots can be highly performative, and this performance can generate of new appropriations that promote interactivity through procedural performances. Architects of the 1960s and ‘70s conceptualized grand ideas of what this type of interaction might look like, which materialized as novel human-computer interfaces on the architectural scale. The projects designed and executed for this thesis at the Princeton University Embodied Computation Laboratory appropriate this idea of Human-Architecture-Computer Interfaces into the current discourse on industrial robotics. Robotic processes were created to capitalize on the performative capabilities of industrial robots. These processes focused on the physical manifestations of digital data through robotic movements, and in this way provide a more tangible and experiential interface for architects to work with digital information. Using sand as a material for interaction was successful, as the human-sculpted landscapes produced articulated patterns and expressive movements from the robot as it traced optimized road paths and moats around sand castles. The modeling and simulation of rocking chair designs requires further development to incorporate more tangible human input, but the concept could have very real benefits for the future of kinetic architecture and spatial prototyping. All three projects developed for this thesis represent sophisticated bases for future development.

As our built environment gets smarter, laden with more devices and greater connectivity, robotics will become essential to architectural design. Architectural robots will be machines that augment spatial experiences through smartly designed algorithms to sense human inputs and act with efficient and optimized motions. Robots will drive kinetic building elements and rearrange objects in space according to sensed behavioral trends and user requests. The question is how, and it begins by proposing an appropriation of robotics that does not try to replace technologies and work flows we have already established, but to use available robotic tools for more continuous, user-empathetic purposes. Digital calculations and robotic actuations can achieve more precise movements, faster quantization, and higher repeatability than humans, and robotics provides the entry point for architecture to begin embodying more sophisticated information from the real world.

This thesis contains many projects that revolve around the industrial robot, but given the technical limits and safety concerns of these machines, they are likely just place holders for a next generation of digital actuators. Nicholas Negroponte, formerly of the Architecture Machine Group, believes that the future of intelligent spaces is not electro-mechanical, but genetic, and that in the future we will grow architecture.[107] While it is an intriguing concept, it is clear that any immediate advancements will be electro-mechanical, and there already exist opportunities with industrial robots to begin exploring how this future will operate. The purpose of this thesis is to explore new techniques that break from the paradigm of automation and production to become augmentative and interactive in their own right. Rapid prototyping and physical modeling should not require month-long projects to produce end-effectors and sensed environments, but should be intuitive and usable in a timely and responsive fashion.

Sand castles and moats may not be the future of architectural robotics, but the most wonderful part of building a sand castle is that it does not need to be a solo activity. Robotics in architecture can soon become the ideal collaborator for making; one that relinquishes full design control to the architect, while tidying up and optimizing each design. The ideal is when the robot can sense behavior so robustly that its action become and extension of the designers own hands and thoughts. This thesis presents a basic model of this behavioral sensing through the sensing of material changes, but once the robot can robustly pick up indirect gestural movements, trace habits of making, or even read information directly from our brain waves, then interactivity will become less explicit, and a more natural augmentation of a working process. For this augmentation to be productive, however, the interpretive processes that translate sensed gestures into robotic action require

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[107] Negroponte, personal email correspondence

further consideration and design. In this model, the robot does not produce architecture or replace architects, but enables a more complete interaction between the two.

FIGURES

Chapter 1

1.1 - Bella, Alessandro. Gramazio & Kohler © ETH Zurich. Structural Oscillations. 2008. http://www.dfab.arch.ethz.ch/data/bilder/03_Thumbs/063/081003_063_StructuralOscillations_AlessandraBello_023_TB.jpg

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1.9 - Kruysman, Brandon and Proto, Jonathan. “Synchronous Dissections”. https://vimeo.com/42946021. *Screenshots from video arranged and drawn by Charles Avis.*

1.10 - Bot & Dolly. “Box”. http://cdn.visualnews.com/wp-content/uploads/2013/09/Bot-and-Dolly-Box-Projection-Mapping.png.

1.11 - UCLA Suprstudio Student Reel. Screenshots taken from video: https://www.youtube.com/watch?v=GdrhsG8yrG8. Accessed 18 April 2014.

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1.13 - Avis, Charles. “Depth Modulations. Gramazio & Kohler at ETH”. January, 2014.

1.14 - Avis, Charles. Human Grunt Work in Fabrication. January 2014.

1.15 - Gramazio & Kohler © ETH Zurich. “Smart Dynamic Casting”. 2014. http://www.dfab.arch.ethz.ch/data/bilder/03_Thumbs/134/140110_134_SquareColumn_EL_010_TB.jpg

Chapter 2

2.1 - Cover of SOFTWARE Information Technology: Its New Meaning for Art. New York: The Jewish Museum, 1970.

2.2 - Image of Seek in SOFTWARE Information Technology: Its New Meaning for Art. New York: The Jewish Museum, 1970. page 21.

2.3 - Price, Cedric. Fun Palace. http://citymovement.files.wordpress.com/2012/03/screenshot-2012-03-24-at-9-36-45-am.png?w=470

2.4 - Price, Cedric. Fun Palace Plan. From the Cedric Price Archive at the CCA. http://restance.wordpress.com/2011/11/10/fun-palace/

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2.6 - Price, Cedric. Generator Modeled in Cubits. Undated. From Generator document folio, DR1995:0280:653, CPA. From Architectures of Information, a Dissertation by Molly Steenson at Princeton University. April 2014.

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2.11 - Line Drawings by Charles Avis.

Images from left to right:

2.11.1 - Jokic, Sasa. "Mataerial". 2013. http://www.mataerial.com/

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2.11.3 - Avis, Charles. “SandCastle”. 2014.

2.11.4 - see fig. 1.8.

Chapter 3

3.1 - Ishii, Hiroshi, C. Ratti, C. Piper, Y. Wang, A. Biderman, and E. Ben-Joseph. “Sand-Scape”. Image from BT Technology Journal Vol 22, no. No 4 (2004): 287-297.

3.2 - Underkoffler, John et al. “Luminous Room.” Image from Proceedings of SIGGRAPH (1999).

3.3 - 3.19 - All remaining figures in Chapter 3 were produced by Charles Avis at the Princeton University Center for Embodied Computation. 2014.

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