Biologically Inspired Digital Fabrication

by

Sarah Han

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ABSTRACT

Objects and systems in nature are models for the practice of sustainable design and fabrication. From trees to bones, natural systems are characterized by the constant interplay of creation, environmental response, and analysis of current structural constituents, as part of a larger dynamic system. In contrast, traditional methods of digital design and fabrication are characterized by a linear progression of three main stages: modeling (digital generation in the digital domain), analysis (digital mapping of the physical domain), and fabrication (physical generation of the digital domain). Moving towards a system process where modeling, analysis, and fabrication are integrated together for the development of a dynamic process will transform traditional fabrication technology and bring about the creation of sustainable and more efficient synthetic environments. Integration of modeling, analysis, and fabrication into one fluid process requires the development of a fabrication platform with capabilities for real time control. This thesis explores and investigates the creation of a framework for real time control of industrial robotic arms as part of a multipurpose fabrication platform.

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1. Introduction and Motivation

1.1. Overview

Natural systems and objects found in the world of nature are testaments to the practice of sustainable design and fabrication. These natural systems are characterized by the constant interplay of creation, environmental response, and analysis of current structural constituents, as part of a larger dynamic system. As exploration of the world of digital design and fabrication progresses there is growing desire to transform traditional fabrication technology and bring about the creation of sustainable and more efficient synthetic environments by drawing inspiration from natural systems. This thesis explores and investigates the creation of a framework for real time control of industrial robotic arms as part of a multipurpose fabrication platform as a way to create the capabilities for an integrated fluid fabrication process that is no longer constrained to a linear process flow.

1.2. Nature Case Studies

Nature's sustainable creations can be found all around us. From the bones in our bodies to the trees found in the forest, natural forms and materials provide us with examples of objects and systems that have endured the passage of eons. The study of nature's forms and materials has aided in the achievements of countless scientific discoveries, and its influence can be found throughout society as whole, including in that of synthetic environment design. It is with respect to the design and fabrication of buildings and systems that we look to nature for inspiration.

Trees are one of nature's creations that are complex systems exhibiting the influence of its environmental surroundings. Trees are shaped by and exposed to a variety of influences. Natural forces such as winds and in addition to their own weight result in stress and strain, which alter the overall shape and structure of the tree to adapt to its unique environment [1,2]. Furthermore, natural systems are also characterized by their constant dynamically changing structural differences at the micro scale. For example, trees have cellulose fibers that change shape in response to external forces. This shape change is exhibited "as mechanical reorientation occurs on the cell walls (local level), the tissue (regional level), and the trunk (global level)" [1,2,3,4].

Bone is another natural creation that also exhibits a change in material properties over time. Bone is composed of mineralized collagen fiber and exhibits changes in structure over time. Parts of bone can be replaced in response to time, stress, and strain. Furthermore, the density of bone material also varies depending on the various influences present during the period of bone formation [1,2,3].

1.3. Advantages of Dynamic Fabrication

Structures found in nature are characterized by the response of the formative process to the forces and loads that act upon it, resulting in a variation of design for each and every creation. Variations in design can vary in magnitude from the slightly different shapes of leaves or the difference between a heart muscle cell and skin cell as cell differentiation occurs in a single cell zygote to the multicellular human adult. Furthermore, the design process in natural systems is an ever-changing, never-ending, complex dynamic process. One has only to think of biological systems that are able to detect and repair localized structural damage to exhibit this complex dynamic process [1]. It is this idea of a dynamic process, which occurs in nature that we hope to translate to traditional methods of digital design and fabrication to create a new approach to fabrication, dynamic digital fabrication.

Traditional methods of digital design and fabrication are characterized by a linear progression of independent stages. The typical design process makes use of computer aided design and is characterized by three main stages: modeling (digital generation in the digital domain), analysis (digital mapping of the physical domain), and fabrication (physical generation of the digital domain), shown in figure 1a [1]. In contrast, dynamic digital fabrication would move towards a system where modeling, analysis, and fabrication are integrated together for the development of a dynamic process that moves closer to the sustainable practices of nature, shown in figure 1b. This shift to an integrated design process allows for a dynamic approach to fabrication that would allow for the creation of structures via one fluid composite process. Development of a dynamic process will transform traditional fabrication technology, bringing about the creation of more sustainable and efficient synthetic environments embodying the essence of nature's sustainable creative processes.

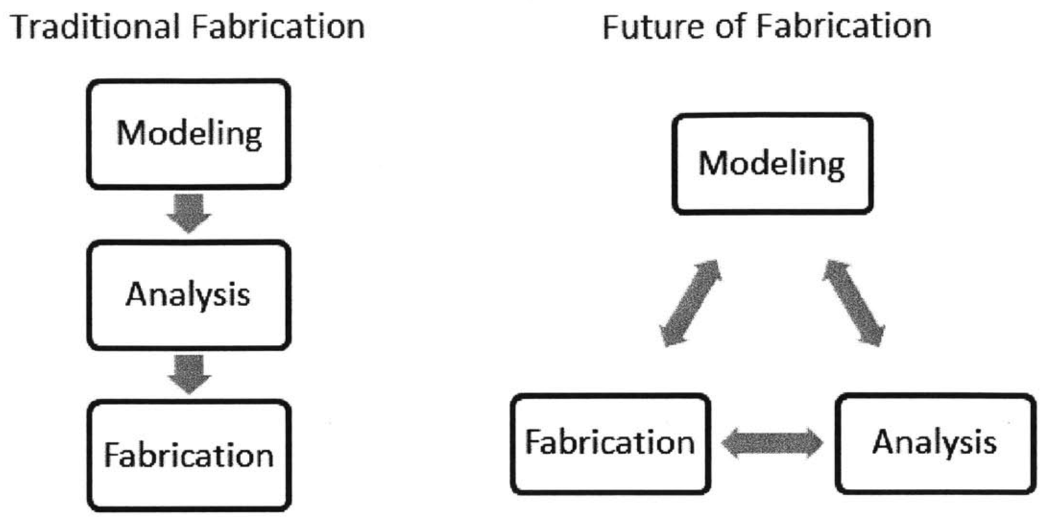

Figure 1. (a) Traditional fabrication processes are characterized by a linear progression of modeling, analysis, and fabrication. **(b)** We envision the future of fabrication as a process that encompasses a constant interplay between modeling, analysis, and fabrication.

1.4. Thesis Overview

Incorporation of modeling, analysis, and fabrication into one cohesive process requires the integration of sensing modalities in conjunction with a fabrication platform that has the potential for dynamic updates. Chapters 2-4 provide background information to provide context for digital fabrication, related research, and the potential for the use of industrial robotic arms in fabrication. Chapter 2 describes current technologies used in digital fabrication. Chapter 3 looks at research efforts in digital fabrication, the potential to use industrial robotic arms for fabrication, and the potential to use digital fabrication technology in the construction industry. Chapter 4 talks more in depth about industrial robotic arms. Chapter 5 describes the current state of research in real time control for industrial robotic arms and talks about the limitations and potential benefits. Chapter 5 also details the research done to explore and investigate the creation of a framework for real time control of industrial robotic arms as part of a multipurpose fabrication platform.

2. Digital Fabrication

Conventional approaches to digital fabrication can be grouped into three main categories: additive, formative, and subtractive manufacturing. Additive manufacturing, also referred to as layered manufacturing, or rapid prototyping transforms digital models (e.g. CAD model) into three-dimensional objects. A digital model is divided into thin layers, or cross-sections, which are then fabricated via a layer-by-layer process [5,6,7]. Subtractive fabrication uses techniques such as Computer Numerical Control (CNC) cutting, also referred to as 2D fabrication, and CNC milling. CNC cutting involves the removal of two-dimensional components from solids or surfaces via cutting technologies such as plasma-arc, laser-beam, or water-jet [6,7,8]. CNC milling is a subtractive fabrication technique used for the removal of specified volumetric quantities from solids via multi-axis milling [7,8]. Formative fabrication applies mechanical forces, restricting forces, heat, or steam to form or shape materials [7,8]. Examples of formative fabrication are bending, extrusion, thermoforming, and molding [6].

These fabrication techniques are all characterized by a linear progression of processes to reach an end product. The typical design process makes use of Computer-aided Design (CAD) and is characterized by three main stages: modeling (digital generation in the digital domain), analysis (digital mapping of the physical domain), and fabrication (physical generation of the digital domain) [1]. Figure 2 depicts an example of the linear process required to design and create a cup using additive manufacturing technology.

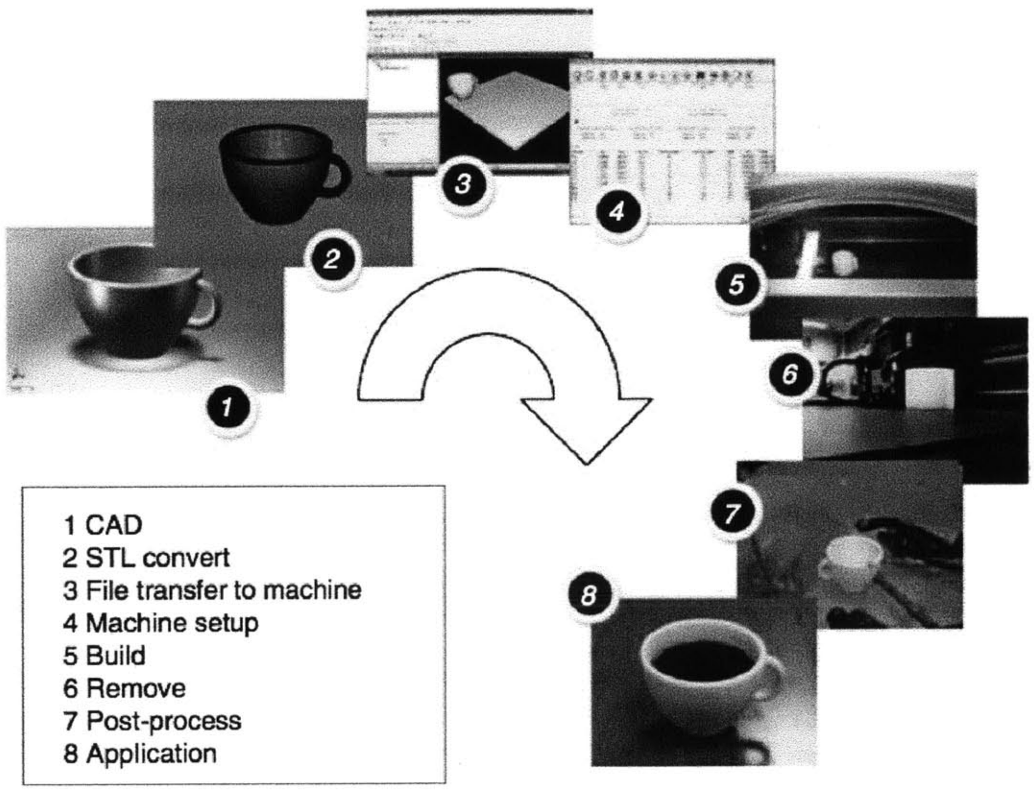

Figure 2. Depiction of linear process flow required to design and create a cup using additive manufacturing technology [5].

3. Current Research in Digital Fabrication

3.1. Overview

The reach of digital fabrication is constantly expanding, encompassing a plethora of potential possibilities and opportunities for a wide range of use. Ongoing research and development of digital fabrication technologies has resulted in applications across many different fields such as biomedical engineering, medicine, aerospace, automotive, art, architecture, and design [6,7,9,10,11,12].

One particular area of development for fabrication technologies is in the field of architecture and design. The research done by Mediated Matter Group at the Media Lab explores "how digital and fabrication technologies mediate between matter and environment to radically transform the design and construction of objects, buildings, and systems." Research in the Mediated Matter Group aims to address the goal of enhancing the relationship between natural and man-made environments. Exploration and development of fabrication technologies within the group has resulted in the development of novel methods for construction such as the Print-in-Place construction process and the development of a multipurpose fabrication platform using a robotic arm.

Other research in the application of fabrication to construction by various groups has resulted in projects such as D.Shape, 3D Concrete Printing, and Contour Crafting [13,14,15].

This chapter focuses on the ongoing fabrication research done by the Mediated Matter group, specifically the Print-in-Place construction process, the multipurpose fabrication platform using a robotic arm, and informed fabrication.

3.2. Construction-Scale Digital Fabrication

One application of digital fabrication to construction is the Print-in-Place construction process developed by Steven Keating. The Print-in-Place construction process uses a robotic arm to print an insulative, rapidly curing spray foam mould which is then used to cast concrete [16]. Figure 3(a) shows an example of a printed mould and casting a mould with concrete. This process can be used to produce building-scale structures and allows for integration of other features such as embedded objects for plumbing, rebar, or electrical wiring or milled designs, as shown in figure 3(b) [16]. Figure 3(c) shows a computer rendering of the Print-in-Place process using a robotic arm attached to a crane.

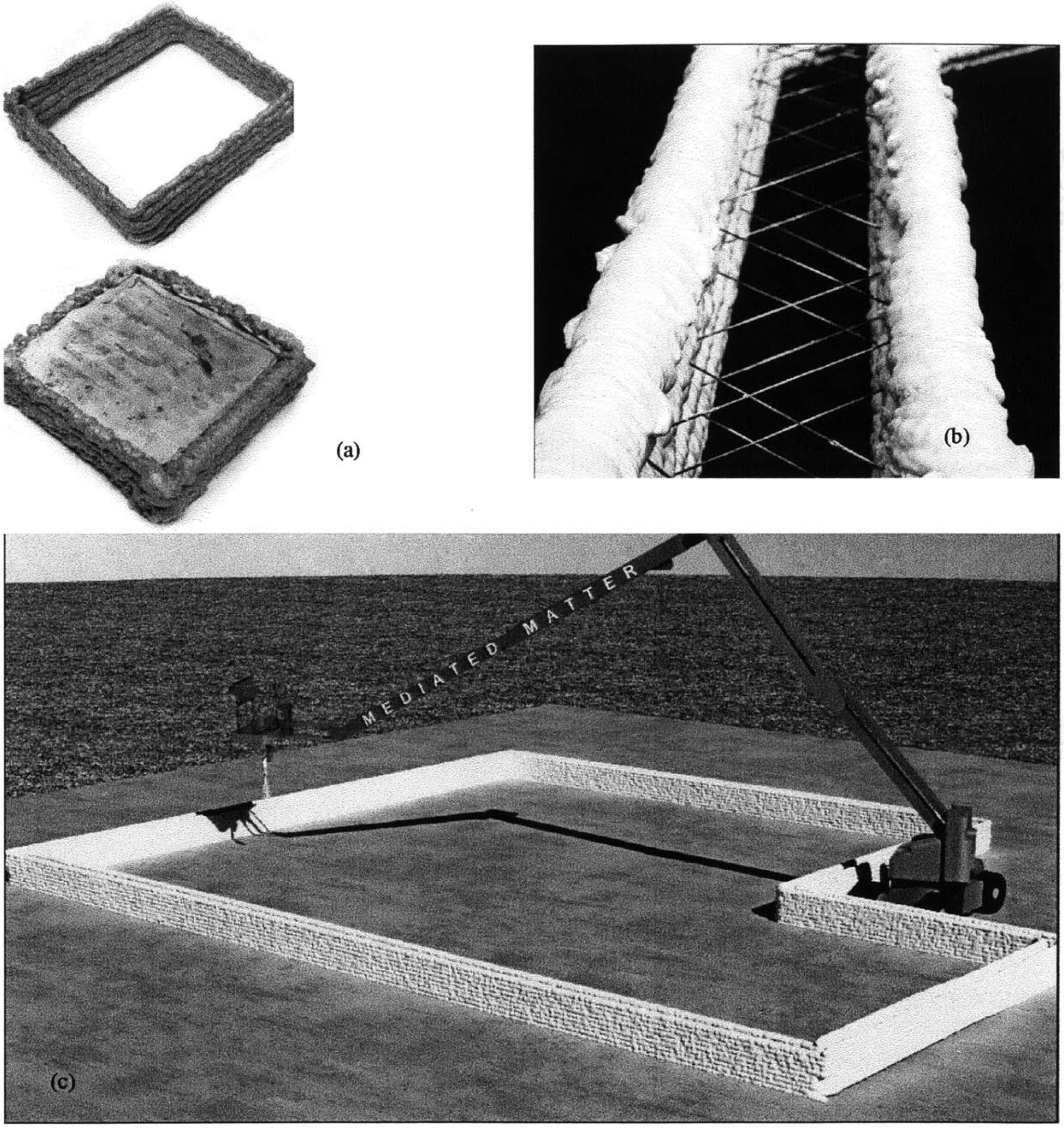

Figure 3. (a) An example of the Print-in-Place process, an insulative, rapidly curing spray foam mould is printed via a robotic arm. Afterwards, the mould is used to cast concrete. **(b)** Integration of features such metal reinforcement rods to printed moulds is possible. **(c)** Rendering of robotic arm platform for printing polyurethane wall mould. [16]

3.3. Multi-Purpose Fabrication Platform

With the use of an industrial KUKA robotic arm Keating developed the first multipurpose robotic arm fabrication platform capable of all three main categories of fabrication: subtractive, additive, and formative [16,17]. Keating demonstrated the use of a robotic arm as a platform for 3D printing, an additive fabrication technique using an ABS print head. Formative fabrication was demonstrated by attaching a holder for sculpting tools to the robotic arm and creating sculpted modeling clay moulds. These moulds were then used to cast urethane plastic objects. Subtractive fabrication was enabled via a robotic arm with the attachment of a rotary tool and milling bits to mill polyurethane foam, ABS, medium-density fiberboard, and modeling wax [16].

3.4. Immaterial and Informed Fabrication

Keating also introduced the concept of Immaterial and Informed Fabrication. Immaterial fabrication is a concept "where designs are produced by changing material and environmental properties without mechanical forces" [16]. For example, Keating creating light paintings using an LED attached to a robotic arm, shown in figure 4(a). Informed fabrication is defined as a "combination of immaterial sensing and physical fabrication, where environmental feedback contributes to the finished design product" [16].

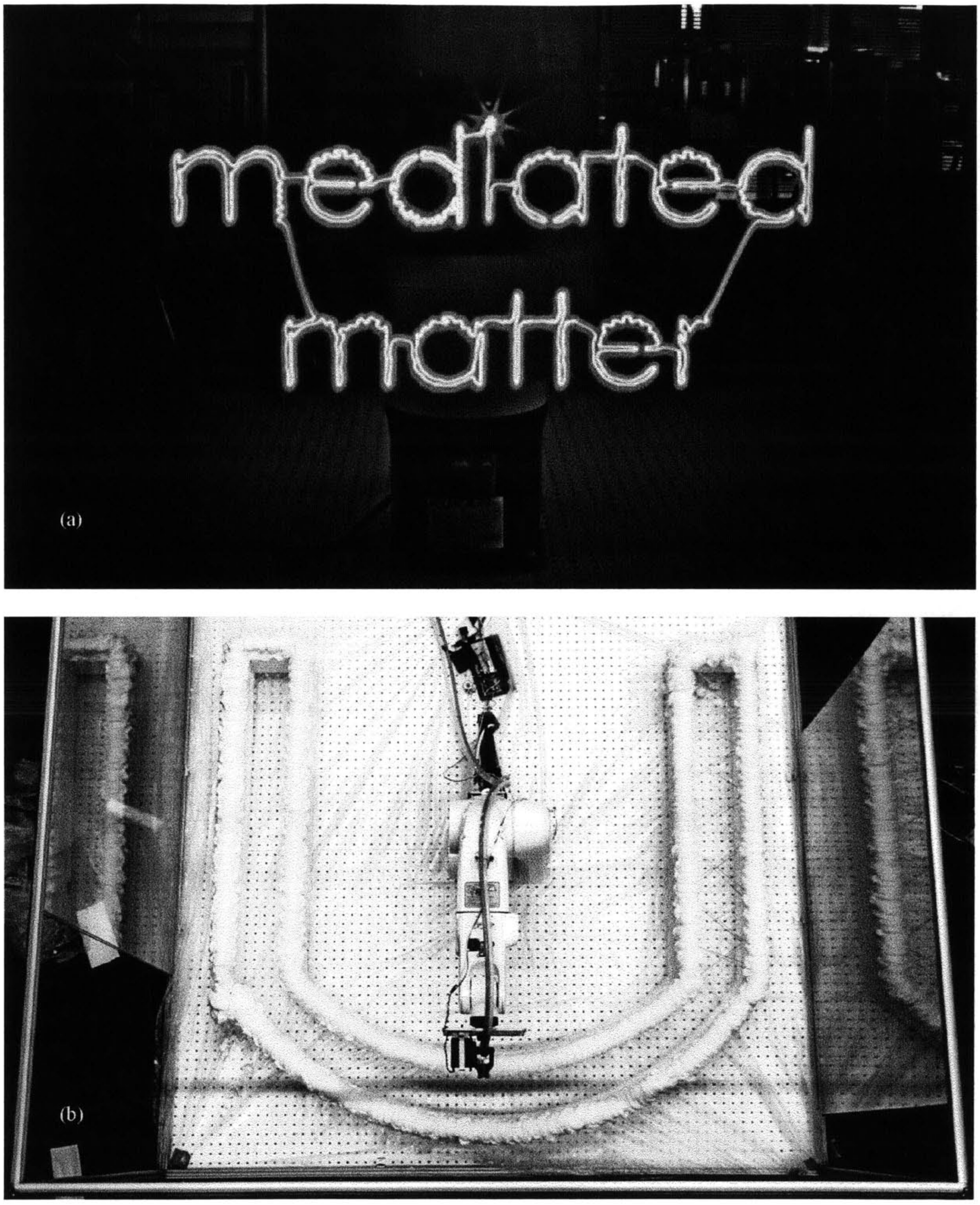

Figure 4. (a) A light painting created using a robotic arm with an attached LED and captured using long exposure photography **(b)** Robotic arm platform used to print a polyurethane wall mould [16].

3.5. Summary

The application of digital fabrication to the field of construction has the potential to transform the construction industry. Fabrication technologies create the possibility for manufacturing complex structures with greater structural integrity, less material waste, a reduction in human labor, and an overall reduction in build time. Potential benefits for more efficient mass customization of buildings also exist. Research in the Mediated Matter group focuses on the potential for the use of industrial robotic arms as a multipurpose fabrication platform for construction and other applications. The following chapter gives a brief history of robotic arms, discusses the potential for the use of industrial robotic arms for fabrication, and describes the robotic arm system used by the Mediated Matter group to provide context for the research done on real time control of a KUKA robotic arm.

4. Robotic Arm

4.1. Overview

The concept of robotics reaches far back in history to ancient legends and myths. Accounts of robot-like devices appear as early as 350 B.C. in ancient Greece with the description of "a strange machine that... was capable of flying more than 200m, using some type of jet propulsion..." [18]. Robotics has evolved over the years aided by advances in technology to include a wide range of functionality and features such as graphical interfaces, virtual robot environments, and digital control loops for better actuator control [18]. Furthermore, there is great potential for the use of robotics in digital fabrication.

Modern robotics is comprised of two main categories, service robots and industrial robots [19]. The International Organization for Standardization (ISO) defines industrial robots as "an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications," while service robots are defined as "a robot which operates semi- or fully autonomously to perform services useful to the well-being of humans and equipment, excluding manufacturing operations." [19].

Industrial robotics is a continuously expanding sector of the robotics market. According to the International Federation of Robotics, as of 2011, the value of the industrial robot market was an estimated $8.5 billon, including the cost of software, peripherals and systems engineering, the worldwide market value is an estimated $25.5 billion [19]. The use of industrial robots spans a wide range of industries as shown in figure 5.

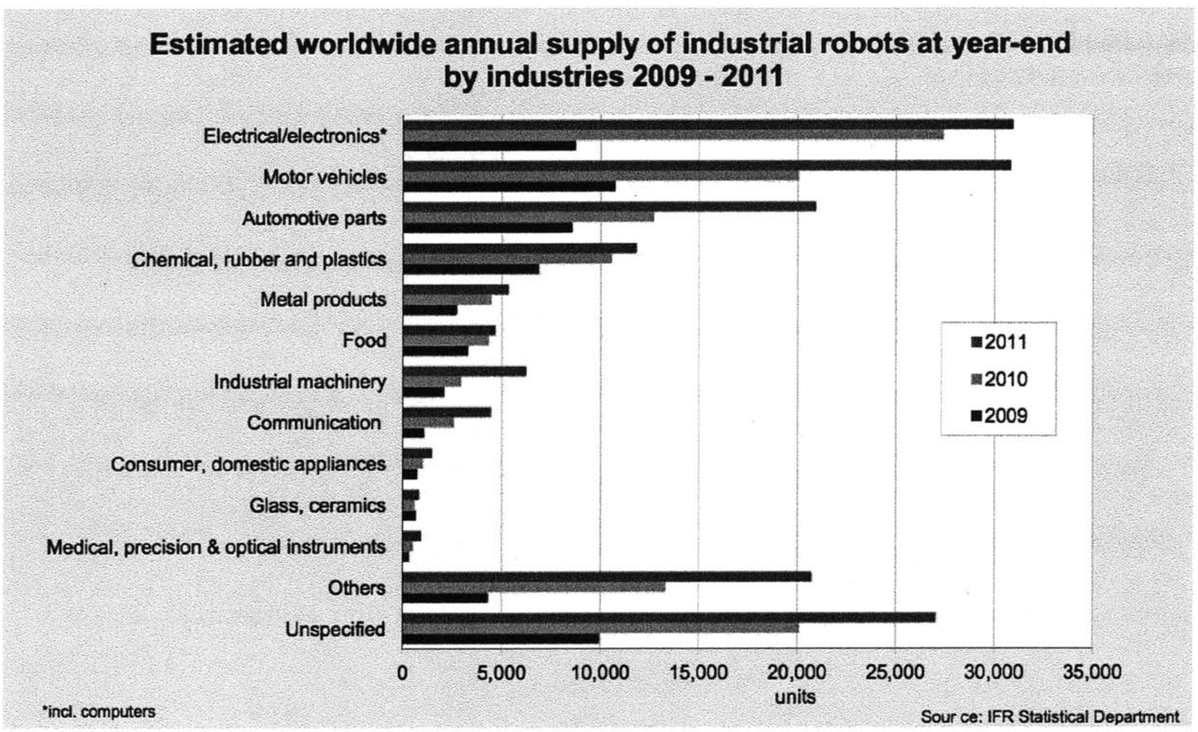

Figure 5. Estimated worldwide annual supply of industrial robots at year-end by industries 2009-2011 [19].

Although there is widespread use of industrial robots, their use is mostly restricted to automation and manufacturing processes, which require repetitive, specified precise motion for task completion [18,21]. However, industrial robots have the potential for a much richer spectrum of complexity and range of tasks. Robotic arms are ideal for digital fabrication due to factors such as flexibility, the ability to be equipped with different end-effectors, potential for customized design, speed, and options for use as an input or output device [16,20,21]. Industrial robotic arms have been repurposed for a variety of projects with applications in various areas such as interactive art, furniture design, bricklaying, surgery, and customized roller coaster rides [20,22,23,24,25]. As mentioned in the previous chapter, research efforts by the Mediated Matter group have demonstrated that the robotic arm can be used as a multipurpose fabrication platform capable of all of the main fabrication categories: additive, subtractive, and formative [16]. This chapter describes the robotic arm used by the Mediated Matter group and the following chapter examines real time control for the robotic arm and discusses limitations and the creation of a framework for real time control.

4.2. KUKA Robotic Arm

The robotic arm system used for research in the Mediated Matter Group at the MIT Media Lab is based on a KUKA KR5 sixx R850 six axis robotic arm, shown in figure 6. The KUKA KR5 is an industrial robotic arm with manipulation capabilities in both the Cartesian and angular domain. The robotic arm weighs 29kg, has a reach of 855mm, speeds of up to 2m/s with a footprint of 200mm x 200mm [27].

Communication with the arm is done using a KUKA KR C2 sr controller. The KUKA robotic arm uses the KUKA Robot Language (KRL), a propriety programming language common to all KUKA products. Previous research done with the arm used code uploaded to the controller and did not include real time control for the arm due to difficulties with interfacing with other common programming languages.

Figure 6. KUKA KR5 sixx R850 6 axis lightweight robotic arm [26].

4.3. Summary

Robotic arms have great potential for use in digital fabrication due to its flexibility, versatility, speed, precision, and possibility to attach a wide variety of end effectors. However, the use of propriety programming languages for industrial robotic arms has created a significant software and programming barrier for widespread use.

5. Real-Time Control

5.1. Overview

Creation of a system capable of large-scale three-dimensional printing for use in construction and architecture, potential exploration of concepts such as silk-based building skins, or building composite structures which incorporate their surrounding environment all potentially require an integrated autonomous sensing system capable of response to changes in the surrounding environment. An integrated sensing system would also be able to interact with dynamic environmental stimuli, creating novel composite structures through the use of a system cognizant of change. Furthermore, the integration of real-time control with current digital fabrication techniques will enable process control and set the stage for fabrication of novel structures.

For example, the use of real-time control with the Print-in-Place construction process will enable process control for material variation (e.g. spray foam) and for environmental noise and variation. Since systems such as the Print-in-Place construction process are designed for use in settings such as outdoor construction sites where strict environmental constraints cannot be enforced, real-time control is crucial for optimal functionality. Even for systems where strict control of environmental factors can be achieved error correction can be enabled via real-time control.

5.2. Benefits

In the Print-in-Place process, material variation due to factors such as temperature, foam expansion, and foam layer height can introduce systematic error. In particular, incremental differences in foam layer height can result in a cycle of positive feedback. The Print-in-Place process prints consistently uniform foam layers which when layered can achieve building scale wall heights. Through the use of a robotic arm with a foam printing attachment, the arm is programmed to move a fixed height and distance for each layer. As overall structure layer height increases, incremental variation in layer height due to incremental changes in the distance from the printer head to the top of the printed wall slowly increases or decreases. This results in an increasingly thicker or thinner foam spray, which in turn creates inconsistent foam layer height. This cycle of positive feedback in layer height requires that the system must be constantly monitored for change in spray nozzle height and manually updated by repositioning the arm. This can be a tedious, somewhat imprecise task that impedes the development of an autonomous printing system for construction. Real-time control will allow for autonomy of the printing system and process control for the Print-in-Place process.

Another example that shows the potential benefits of real time control for fabrication is the use of Makerbot 3D printers. Roughly a quarter of the items printed using a Makerbot 3D printer in the Mediated Mater lab have to be re-printed at some point due to an error in printing. Incomplete layer adhesion or warping of the printed object, such as the object detachment from the build platform, is a common problem that currently has no solution other than to re-start and re-print the entire object. However, with the addition of real-time control, a user could potentially adjust the printing conditions to account for printing errors as they occur. This would save time and material costs since print jobs would not necessarily have to be completely re-done or re-started.

5.3. Limitations

Real time control for robotic systems is a widely researched concept. The plethora of research on real-time control for robotic systems has resulted in a multitude of projects based on the subject. Research projects aimed at autonomous real time control have demonstrated the use of various sensors, control logic, and integration of systems for interests such as visual tracking for robotic systems such as the widely popular quadcopter [28,29,30,31,32]. Other projects such as the Real-Time Robotic Hand Control using Hand Gestures, which used a PUMA industrial robotic arm programmed with VAL, have shown the use of real time control for manufacturer specific industrial robotic arms [33]. Although, there have been projects with real time control for industrial robotic arms, most of these projects involve programming via robot specific languages such as VAL for PUMA robotic arms and KRL for KUKA robotic arms. Some robotic arm manufacturers, such as KUKA have realized the need for easier programming interfaces and produced new robotic arms such as the KUKA Lightwieght Robot which has a new PC-based KUKA robot controller which eliminates the need for programming in favor of teaching the robot by guidance [34,35].

Overall, translating the success of real time control mechanisms used in robotics projects to manufacturer specific industrial robotic arms has proven difficult due to the use of manufacturer specific proprietary programming languages, which hinder the use of open-source platforms and third-party software.

Current research efforts such as the Robot Operating System (ROS), the Orocos Project, the Kuka Control Toolbox (KCT), and the KUKA parametric robot control for Grasshopper show promise for moving towards open-source control [36,37,38,39,40]. The Robot Operating System (ROS) is an "open-source, meta-operating system for your robot" and provides libraries and tools for software developers to create robot applications [36]. The Orocos Project provides open source robot control software in the form of C++ libraries [37,38]. The KUKA Control Toolbox provides MATLAB functions for motion control of KUKA robot manipulators [39]. The KUKA parametric robot control for Grasshopper allows a user to program through a parametric modeling environment to generate robot control files [40].

The use of the software and tools created by these research projects require familiarity with some form of programming such as C++ or Matlab, or only provide capabilities for offline programming [38,39,40]. Furthermore, the capability for easily expanding these programming interfaces and the software architecture to include multiple sensors of varying types is limited without rebuilding and restructuring the control system [36,41]. In order to create an environment where not only programmers and engineers, but also designers and the general population can participate in real time control of robotic arms for digital fabrication and other uses, there is still much work to be done.

The rest of this chapter explores the creation of a framework for non-programmer user-friendly real time control of KUKA industrial robotic arms. Specifically, real time control of the robotic arm via different sensing modalities was explored through the design, implementation, and integration of graphical user interface (gui) components and input devices (sensors and sketchpad).

5.4. System Architecture

5.4.1 Communication Scheme and Hardware

To explore and investigate the creation of a framework for real time control of industrial robotic arms as part of a multipurpose fabrication platform a graphical user interface (gui) was designed and implemented with the integration of a sensor module. This section describes the overall system setup that was created to allow for real time control.

To allow for real time communication the Robot Sensor Interface (RSI) software package for the KUKA robotic arm was purchased and installed. RSI enables real time control for the arm by allowing communication between the robot controller and an external system via Ethernet. To allow for communication between a remote computer and the robot controller a python server script, written by Ilan Moyer and Steven Keating, was used. The python server script also allowed for interfacing with other programming languages. Figure 7 shows the overall communication scheme between a remote computer and the KUKA robot arm that includes:

1) a remote computer running kuka.py a python server script
2) the KUKA Robot Controller (KRC)
3) the KUKA robotic arm
4) a sensor module

A connection is established between a remote computer and the KUKA robot controller via Eth.RSIXML (a KUKA software package). The KRC runs PythonRSI.src, KRL code, which manages the data exchange with the robotic arm and runs the client for the Eth.RSIXML. The python server script also communicates with a Java client using the TCP/IP protocol. The Java client also communicates with a sensor module via a serial port.

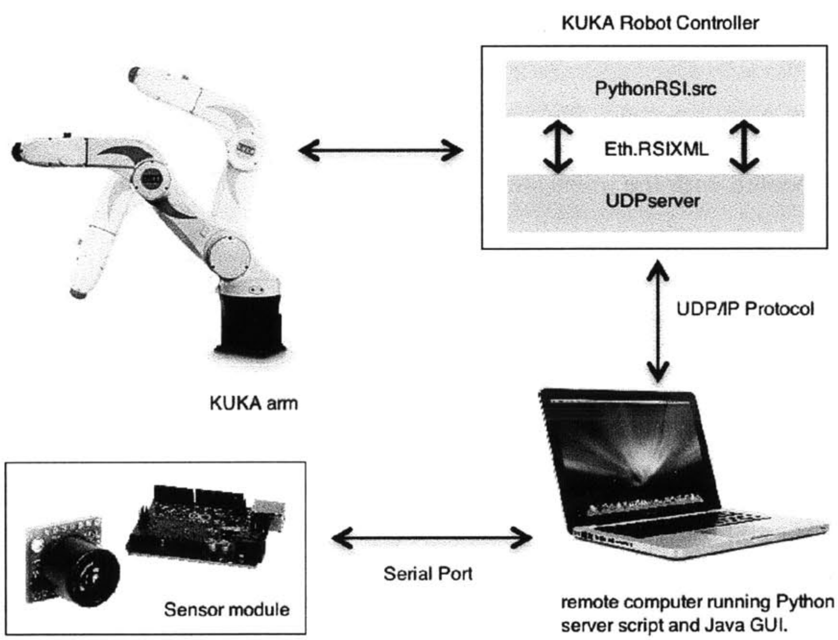

Figure 7. Communication scheme for real time control between a KUKA robot controller, a remote computer, and a sensor module.

In order to add the functionality possible for process control, real-time control via sensors was desired. A sensor module for distance sensing shown in figure 8 was connected via serial port to the Java client and consisted of an Arduino uno board and the following three sensors:

- An ultrasonic sensor (Maxbotix HRLV-EZ4) with 1mm resolution and sensing up to 5 meters

- An Infrared Proximity Sensor (Sharp GP2Y0A21YK) with sensing for 10cm-80cm
- An Infrared Proximity Sensor (Sharp GP2D120XJ00F) with sensing for 3cm-30cm

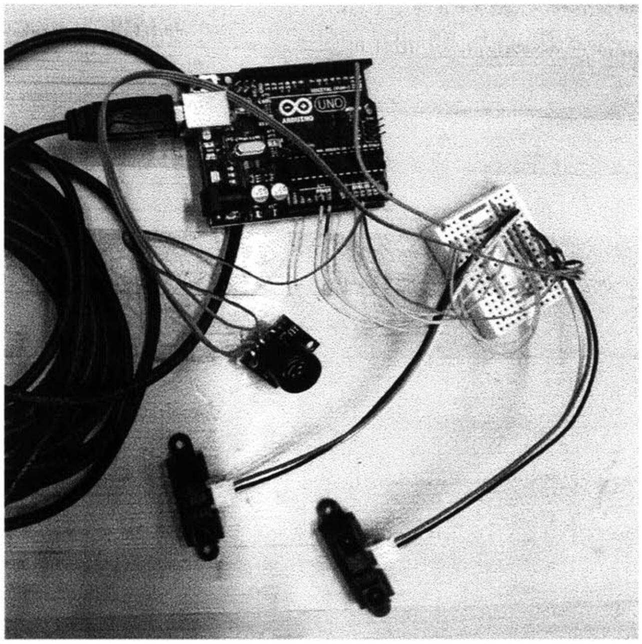

Figure 8. Sensor module for distance sensing.

5.4.2 Graphical User Interface (GUI)

To promote ease of use for users of all backgrounds, a Java based graphical user interface (gui) was designed and created to enable easy real time control of the robotic arm for people of all backgrounds. Figure 9 shows the basic functionality of created graphical user interface (GUI). The client GUI allows the user to:

- Jog each of the robot joints in any direction.
- Move the end effector to specific coordinates and orientations.
- Import a file with pre-determined points and have the robot move to each point.

- Integrate sensor data for error correction & motion detection.
- Draw with the arm via a sketchpad.

Importing a file, changing the settings, adding a sensor, or drawing via the sketchpad could all be easily accessed through the file menu located on the top left corner of the gui.

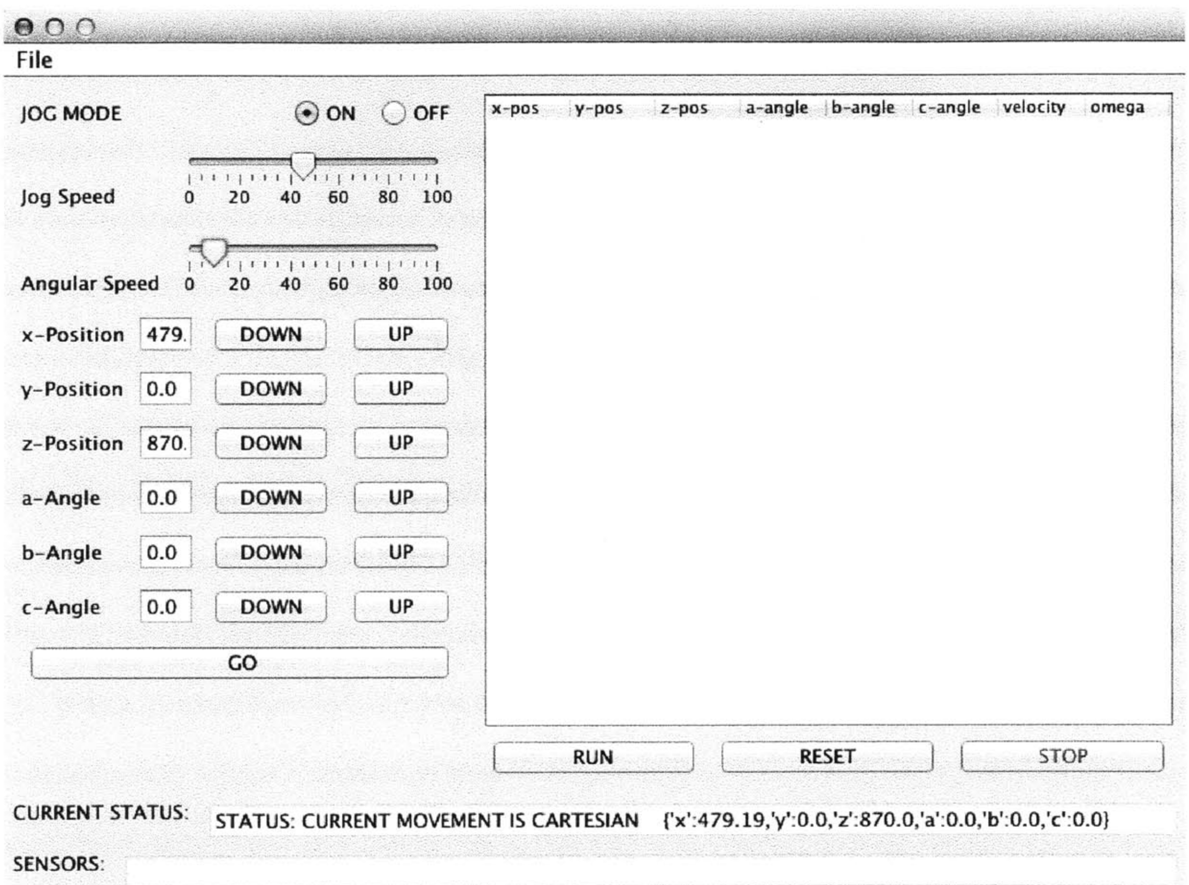

Figure 9. Graphical user interface designed for use with the robotic arm.

5.5. Results and Discussion

The viability for real time process control of processes such as the Print-in-Place construction process was demonstrated using the sensor module shown in figure 8. The sensor module was attached to the end of the robotic arm, shown in figure 10. Using the gui, different ideal distances were specified and tested for behavior using a smooth foam board and a printed foam block. As expected the gui was able to receive and display sensor distance readings and adjust the robotic arm's position in real time to compensate for the movement of the foam board. When the board was either too far or too close to the robotic arm and sensor, the arm would move closer or farther away in order to remain at the previously specified ideal distance.

Figure 10. Robotic arm with attachment for sensor module.

The potential for real time control of the robotic arm for more complex behavior via the gui was demonstrated by using the robotic arm as a drawing tool. Figure 11 shows the setup, which included an attachment to hold a drawing device for the robotic arm and a drawing surface. Using a software sketchpad via the gui, shown in figure 12, a user can draw with the arm by drawing on the sketchpad. Figure 13 shows a close up of a drawing done with the robotic arm to match the user created drawing in figure 12. Using a maximum speed of 1500 mm/s resulted in responsive real time control of the arm via the sketchpad. The robotic arm was able to reliability reproduce drawings in real time without significant lag.

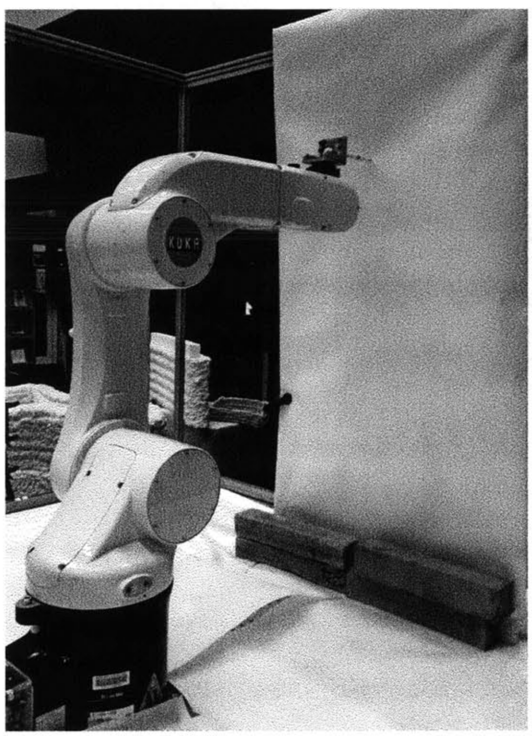

Figure 11. Arm with attachment for marker and drawing setup.

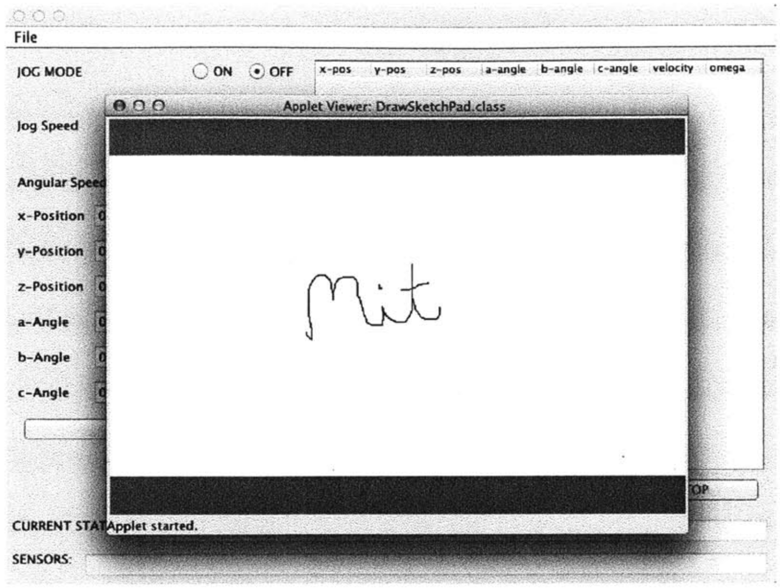

Figure 12. A user can draw with the arm via the sketchpad.

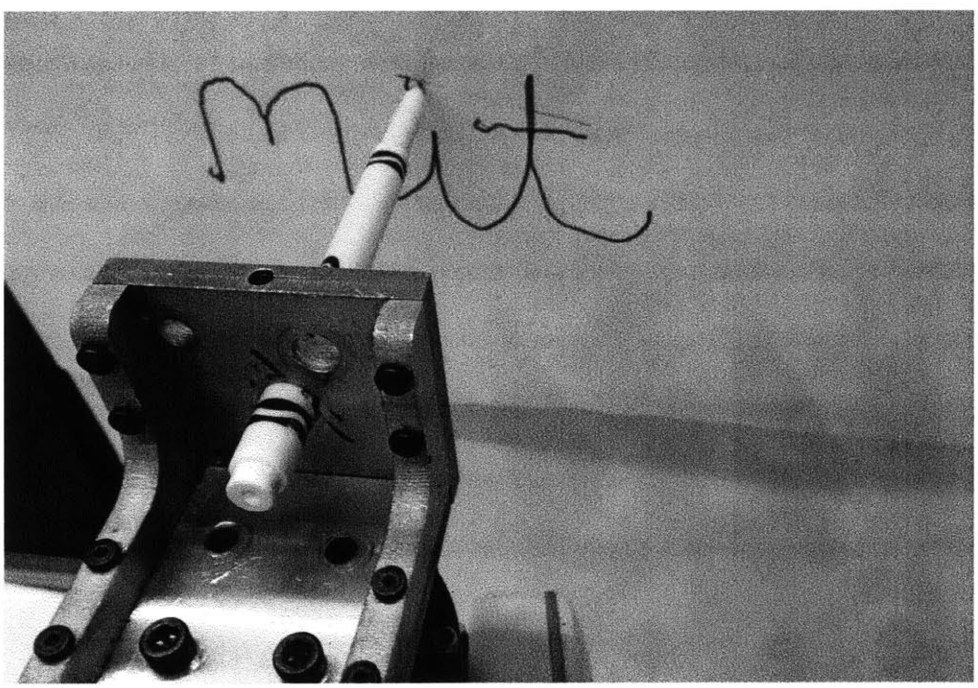

Figure 13. Close up of writing done with marker using real time control for the robotic arm via the gui sketchpad.

The modular nature of sensor integration and interface design allow for the ability of programmers to easily customize the interface and real-time control components to their needs. This setup allows for easy open source type integration of any number of input and output devices that can be used for real-time control of the arm. Users can easily add any number of sensors (or other input/output devices) to interface with the arm and specify factors such as a distance range that the arm should keep while completing a task using a sensor or multiple sensors. The simple sensor integration of the gui also creates the possibility for the use of the robotic arm system by users with no prior programming experience.

6. Conclusion and Contributions

6.1. Contributions

In this thesis, I have explored, developed, and designed a framework for easy integration of sensors for real time control of industrial robotic arms as part of a multipurpose fabrication platform. This system has laid the groundwork to allow for the capability to use an integrated fluid fabrication process that is no longer constrained to a linear process flow. Sensor integration allows for dynamic behavior based on environmental stimuli.

The following contributions were made:

- Designed, developed, and created a system for easy integration of sensors for real time control of an industrial robotic arm as part of a multipurpose fabrication platform.
- Designed and developed, graphical user interface (gui) components to promote ease of use for users with no programming background.
- Demonstrated the use of real time control for error correction.
- Demonstrated the use of real time control for complex behavior by using the robotic arm to draw via a software sketchpad.

6.2. Future Work

In this thesis, I have explored, developed, and designed a framework for easy integration of sensors for real time control of industrial robotic arms as part of a multipurpose fabrication platform. Real time control of the KUKA robotic arm was demonstrated through the use of sensors and a software sketchpad. Future work would include demonstrating the potential for complex multi-process digital fabrication, perhaps through the use of integrating easy gui components for allowing users to switch end effectors based on sensor data. This would allow for more complex processes that could be used for construction scale fabrication. Also, demonstrating real time control via the use of more input and output devices in parallel would add more functionality to the system. Integration of tasks such as switching end effectors and sensor-based motion would allow for an autonomous process where a robotic arm could simultaneously print a foam mould, integrate layers, integrate features such metal reinforcement rods, and perform custom surface detailing.

Furthermore, in order to allow for user customization of features such as the addition of sensors, future iterations of the gui could include a software sensor wizard, which could allow users to customize not only the type of sensor but the specified control logic and behavior associated with each sensor or allow for complex behavior based on multiple sensors. Addition of a simulator that would allow users to simulate arm behavior before sending actions to the arm, and/or record a simulated video of the arm behavior would allow users to easily save and share data.

7. References

[1] Oxman, Neri. "Material-Based Design Computation." Massachusetts Institute of Technology, Dept. of Architecture. 2010.

[2] Oxman, Neri. "Programming Matter." Architectural Design (2012) : 85-99.

[3] Oxman, Neri. "Variable Property Rapid Prototyping." Virtual and Physical Prototyping 6:1 (2011) : 3-31.

[4] Oxman, Neri. "Structuring Materiality, Design Fabrication of Heterogeneous Materials." Architectural Design. (2010) : 78-85.

[5] Gibson, Ian, David W. Rosen, and Brent Stucker. *Additive Manufacturing Technologies*. New York: Springer, 2010.

[6] Pupo, Regiane, Gabriela Celani, and Jose Pinto Duarte. "Digital Materialization for Architecture: Definitions and Techniques." Pro Pratica Profissional e Technologias Digitais. 2009.

[7] Kolarevic, Branko, ed. *Architecture in the Digital Age: Design and Manufacturing*. London, UK: Spon Press, 2003.

[8] Kolarevic, Branko. "Designing and Manufacturing Architecture in the Digital Age." Architectural Information Management: 19th eCAADe Conference Proceedings, 117-123. eCAADe. Helsinki, Finland: Helsinki University of Technology (HUT), 2001.

[9] Laskovski, Anthony N., ed. *Biomedical Engineering, Trends in Materials Science*. InTech, 2011.

[10] Mardones, José, et al. "Using Digital Fabrication on Small Satellite Projects." Small Satellites Systems and Services: The 4S Symposium, 2012.

[11] Lee, M. Y. and C. C. Chang. "Layer-based Abrasive Computer Tomography for Custom Denture Fabrication." 2010 International Conference on System Science and Engineering, 2010.

[12] Richardson, Mark and Bradley Haylock. "The Rise of Additive Manufacturing, Domestic-Scale Production and the Possible Implications for the Automotive Industry." PACE Conference: Computer-Aided Design & Applications, 2012.

[13] Dini, Enrico. "What is D-Shape." Monolite UK Ltd. < http://www.d-shape.com/cose.htm>

[14] Khoshnevis, Behrokh, et al. "Mega-scale Fabrication by Contour Crafting." Int. J. Industrial and Systems Engineering 1 : 3 (2006) : 301-320.

[15] Lim, S., et al. "Developments in Construction-scale Additive Manufacturing Processes." Automation in Construction 21 (2012) : 261-268.

[16] Keating, Steven. "Renaissance Robotics: Novel Applications of Multipurpose Robotic Arms Spanning Design Fabrication, Utility, and Art." Massachusetts Institute of Technology, Dept. of Mechanical Engineering. 2012.

[17] Keating, Steven and Neri Oxman. "Extending an Arm: A Multi-Functional Robotic Fabrication Platform." 2012.

[18] Pires, J. Norberto. *Industrial Robots Programming: Building Applications for the Factories of the Future.* New York: Springer, 2007.

[19] International Federation of Robotics. "Industrial Robot Statistics." 2011. <http://www.ifr.org/industrial-robots/statistics/>

[20] Bonwetsch, Tobias. "Robotic Assembly Processes as a Driver in Architectural Design." Nexus Netw J 14:3 (2012): 483-494.

[21] Agrawal, Naveen. "Robotics." 2009. <http://www.brighthubengineering.com/robotics/26216-introduction-to-robotics/>

[22] Cleland, Kathy. "Mixed Reality Interaction: Audience Responses to Robots and Virtual Characters." Digital Creativity. 21:1 (2010): 30-38.

[23] Hwang, Margaret, Peter Schmitt, and Matt Trimble. Hot Wire Table: Robotic Arm Fabrication. 2010. <http://www.behance.net/gallery/Hot-Wire-Table-(Robotic-Arm-Fabrication)/5095819>

[24] Bodner, J., et al. "First Experiences with the da Vinci Operating Robot in Thoracic Surgery." Eur J Cardiothoracic Surgery. 25:5 (2004): 844-851.

[25] Schaetzle, S., C. Preusche, and G. Hirzinger. "Workspace Optimization of the Robocoaster used as a Motion Simulator." Robotics and Applications, 2009.

[26] KUKA Robot Group. "KUKA Products." KUKA Roboter GmbH. < http://www.kuka-robotics.com/en/products/> (2012).

[27] KUKA Robot Group. "KR 5 sixx R650, R850 CR Specification." Germany: KUKA Roboter GmbH, 2011.

[28] Mason, Julian, Bhaskara Marthi, and Ronald Parr. "Object Disappearance for Object Discovery." Proceedings of the 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems. 2012.

[29] Achtelik, Markus, Tianguang Zhang, Kolja Kiihnlenz and Martin Buss. "Visual Tracking and Control of a Quadcopter Using a Stereo Camera System and Inertial Sensors." Proceedings of the 2009 IEEE International Conference on Mechatronics and Automation. 2009.

[30] Sa, Inkyu and Peter Corke. "System Identification, Estimation and Control for a Cost Effective Open-Source Quadcopter." 2012 IEEE International Conference on Robotics and Automation. 2012.

[31] Olivares-Mendez, Miguel A., Pascual Campoy, Ignacio Mellado-Bataller, and Luis Mejias."See-and-Avoid Quadcopter using Fuzzy Control." Optimized by Cross-Entropy WCCI 2012 IEEE World Congress on Computational Intelligence.

[32] Sa, Inkyu and Peter Corke. "Vertical Infrastructure Inspection Using a Quadcopter and Shared Autonomy Control." Proceedings of the 8th International Conference on Field and Service Robotics. 2012.

[33] Raheja, Jagdish Lal, Radhey Shyam, Umesh Kumar, and P Bhanu Prasad. "Real-Time Robotic Hand Control using Hand Gestures." 2010 Second International Conference on Machine Learning and Computing. 2010.

[34] Schreiber, Gunter, Andreas Stemmer, and Rainer Bischoff. "The Fast Research Interface for the KUKA Lightweight Robot." Proceedings of the 2010 IEEE International Conference on Robotics & Automation. 2010.

[35] KUKA. "Take the Robot by the Hand." <http://www.kuka-robotics.com/en/pressevents/news/NN_060515_Automatica_02.htm>

[36] Robot Operating System. ROS.org. <http://www.ros.org/wiki/> (2013).

[37] The Orocos Project. "Open Robot Control Software." <http://www.orocos.org/> (2013).

[38] Bruyninckx, Herman, Peter Soetens, and Bob Koninckx. "The Real-Time Motion Control Core of the Orocos Project." Proceedings of the 2003 IEEE International Conference on Robotics & Automation. 2003.

[39] Robots in Architecture. "KUKA|prc – parametric robot control for Grasshopper." Association for Robots in Architecture. < http://www.robotsinarchitecture.org/kuka-prc> (2011).

[40] Chinello, Francesco, et al. "The KUKA Control Toolbox: motion control of KUKA robot manipulators with MATLAB." IEEE Robotics and Automation Magazine. 2010.

[41] Kroger, Torsten, Bernd Finkemeyer, and Friedrich M. Wahl. "Manipulation Primitives—A Universal Interface between Sensor-Based Motion Control and Robot Programming." *Robotic Systems for Handling and Assembly*. pp. 293-313. Berlin: Springer, 2010.

[42] KUKA Robot Group. "KUKA Robot Sensor Interface 2.3." Germany: KUKA Roboter GmbH, 2009.

[43] Arduino. "Getting Started with Arduino." <http://arduino.cc/en/Guide/HomePage> (2012).

[44] Rutherford, Jerry. "Using the PUMA 560 Robot: A User's Guide to Basic Operation of the PUMA Arm Robot." 2012.

[45] Schütz, D. and F.M. Wahl, eds. *Robotic Systems for Handling and Assembly*. Berlin: Springer, 2010.

[46] Hopkinson, N., R.J.M. Hague, P.M. Dickens, ed. *Rapid Manufacturing: An Industrial Revolution for the Digital Age*. England: Wiley, 2006.

[47] Willis, Karl, et al. "Interactive Fabrication: New Interfaces for Digital Fabrication." TEI 2011.