Human Interaction-Oriented Robotic Form Generation

Reimagining Architectural Robotics Through the Lens of Human Experience

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Abstract Within the discipline of architecture, the exploration and integration of robotics has recently become an area of rapid development and investment. But with the current majority of architectural robotics research focused primarily around the realms of digital fabrication and biologic form/material optimization, there are few examples of direct translation from human generated data to form and processes, particularly as it pertains to the human experience of, and the interaction with architectural artifacts. Through a series of three case studies each building upon the previous, this paper investigates how the interconnection of secondary, smaller data harvesting/translating robotic systems in collaboration with larger industrial systems can be integrated within the conceptual design workflow to allow for the creation of unique/interactive tools for the materialization of human interaction through design, robotic control, and fabrication.

Keywords Robotic fabrication · Big data · Computation · Robotic manipulation

1 Introduction

Within the discipline of architecture, the exploration and integration of robotics has recently become an area of rapid investment and development [3], [5], [7].

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This exploration in robotics is often limited by the narrow framework of exploration focused around the areas of digital and robotic fabrication. Although robotic fabrication allows for the creation of unique and innovative solutions for more complex construction problems, the appearance of the final resulting artifacts can lack a human touch and can often be easily traced back to a specific tool methodology, material or structural exploration.

Rather than initiating the design process with a desired end resultant (artifact) or set of known robotic processes in mind, this paper asks, “Can conceptual form, tools and processes be generated through the harvesting, translation and utilization of unmediated, human interaction-based data sources?” Through a series of case studies, this paper examines:

1. Human-robot interactive data generation and collection.
2. One-to-one, real-time data translation into 2D artifacts.
3. The conversion of collected data into 3D spatial potentials.
4. The harnessing and translating of collected data in the creation of unique, human interaction-derived industrial robot movements and end-effectors that create a large-scale wound-composite interior installation to be displayed at Ball State University.

Through these case studies, this paper will examine the potential of utilizing interactive robotic data collection and fabrication systems as a design tool that could be utilized to create novel, experience driven design solutions for the initiation of the design process.

2 Data

With the volume of data available at our fingertips growing on a daily basis, understanding innovative and meaningful methods for its utilization within architecture has become an important yet difficult undertaking. Data can enable architects and researchers to comprehend and predict local and global trends based on continuously updated information, but deciphering and filtering which data is relevant and meaningful can become a complex problem. In addition, data selection does not necessarily lend itself immediately to a physical manifestation. Rather, data may suggest the appropriateness of a certain type of solution for a given region, which can then be implemented through other means.

As opposed to investigating the use of such a process to solve specific global problems, this paper explores novel processes for the generation and collection of localized data through human-robot interaction and the direct translation of that data into the production of 2D and 3D tangible artifacts. In order to minimize the number of initial variables, case studies utilized local data generated by uninformed human participants interfacing a robotic drawing machine, rather than harnessing “Big Data”.

2.1 Data Types & Collection Methodologies

With the vast amounts of existing data available and the increasing ease of collecting new data digitally, it can be difficult to choose a specific aspect to inform the design process. Since a direct translation to physical artifacts was a desired outcome for the case studies featured in this project, it was important that the chosen data type could be easily translated into a format understood by various types of robotic systems that function in two or three dimensions. The exact data type and mapping (translation) process employed in each case is discussed with the respective case below.

3 Case Studies

Throughout the course of this research, three distinct case studies were developed as a means of testing the of feasibility of translating global data into a design language. Employing local data arising from simple human-robot interaction, each test built upon the previous and developed the concept of translation as a design tool. Each successive test added complexity and scale resulting in the translation of collected data into:

1. 2D physical artifacts in the form of robotic drawings.
2. Industrial-scale robotic movements with the potential to define visual spatial constructs.
3. 3D physical artifacts in the form of a large-scale, composite-based, industrial robot-fabricated interior installation.

Following, this paper discusses the processes and artifacts created throughout each of these case studies.

4 The Lean Mean Data Harvesting Drawing Machine

The drawing machine was the starting point of this research and became the platform upon which subsequent case studies were developed. The initial focus of development was on the creation of a framework for the direct collection and translation of data arising from an unmediated human-robot interface. While human interaction data could be collected in any number of ways, a simple option was to collect data with the ability to be scaled and mapped onto a spatial coordinate system. Since color data is often represented with three values (e.g. red, green, blue), it lends itself to XYZ coordinate mapping.

A method was developed to collect color data and map it to a Cartesian coordinate system based on an interchangeable translation algorithm. Using webcams and video processing tools including Firefly (for Grasshopper, a visual programming environment for Rhino) and OpenCV (a standard computer vision library), an average color value was calculated for a region of interest at the center of each analyzed frame. To keep the amount of data collected manageable, only one or two frames were processed per second. Subsequently either Grasshopper or Python was used to perform the mapping for each project.

The Lean Mean Data Harvesting Drawing Machine was created to implement this methodology and consisted of a three-part system:

1. A webcam that collected color data from the surrounding environment and from human-robot interaction.
2. A single-board computer (Raspberry Pi) that translated the collected color data into 2D coordinates for the integrated drawing machine that also stored the color data for use in subsequent tests.
3. A small-scale LEGO and custom component based robot that created 2D artifacts while attracting participants to interact with the machine.

Placed in unassuming public spaces, no explanation of the machine or its translation algorithms was given. Individuals approached and interacted of their own accord while the machine recorded the experiences through drawn lines in 2D space and as recorded data points within an external hard drive.

4.1 Motion Translation Algorithm

During initial data collection sessions the translation algorithm employed involved the following steps:

1. RGB color values were converted to HSB (hue, saturation, brightness) values.
2. The hue spectrum was mapped to a circle such that hue values translated to degrees of rotation, or the orientation of a vector.
3. Saturation and brightness values were summed and mapped to distances from the center of the drawing surface to the edges of the drawing area, providing a magnitude for the vector.
4. The vector, plotted from the center of the drawing surface, pointed to a specific XY coordinate for each color.

4.2 The Drawing Machine

The drawing machine was designed as a simplistic robotic tool that would allow for intuitive human-robot interaction (Figure 1). Constructed of laser cut acrylic, foam core and Plexiglas sheets, the design was concerned with simplicity over precision, providing the opportunity for uncontrolled variables to appear. LEGO Mindstorms robotics components were employed to generate and control movement. LEGO NXT motors were mounted on the upper corners of the acrylic frame and LEGO wheel hubs were used as spools. The monofilament wound around the spools was connected to a drawing “puck”, which was designed to slide across the drawing surface with minimum contact aside from the pen attached through its center.

To convert the XY coordinates provided by the Raspberry Pi to pen movement, a LEGO NXT microprocessor running the LeJOS NXJ open source operating system and a Java-based control program performed another translation, calculating (based on the geometry of the drawing surface) the degrees of rotation that each motor (and associated spool) needed to rotate to result in the correct amount of unspooled filament. The calculations were simple, avoiding the calculus that might be employed in a more precise system.

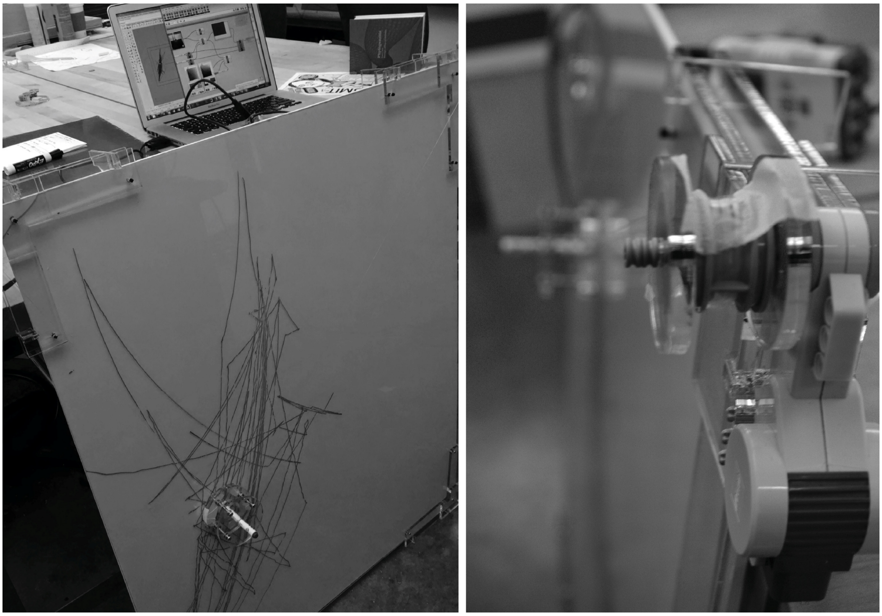

Fig. 1 The drawing machine & Detail of motor and Spool

4.3 User Interaction

Because the drawing machine was constantly receiving and processing input (whether or not any participants were present) and because the webcam picked up subtle variations in light from frame to frame as lighting conditions changed, the machine was almost constantly in motion. Even though most of its movements were small when no one was interacting with the machine, it generated enough noise and movement to catch the attention of many passersby. The machine's response to the presence of people was often dramatic due to the significant changes in color that the camera observed during such periods of interaction. This created additional interest, and at times a large number of people gathered around the machine, some gesticulating wildly to see what kinds of movement they could stimulate. The absence of explanation combined with a clear connection between interaction and movement stimulated curiosity and created a memorable experience for the individuals interacting with the machine.

4.4 Visual Output

The drawings produced by the drawing machine reflect qualities of the environment in which it was placed and of the user interaction that transpired. The example below (Figure 2)was the first drawing generated over an extended period of time, from late afternoon until after dusk. The changing quality of light in the space was tracked by the machine and is evident in the drawing—the location that the pen idled during periods without interaction (producing the densest markings) started out towards the left and migrated to the right over the course of the time the machine was active. The dramatic swoops above and below the center are the direct result of occasions where human interaction was taking place.

Upon completion of a series of tests in several locations, it was deemed that the initial system created for the translation of the data created by human/robot interaction directly into a physical artifact was successful and should be developed further into a 3D system.

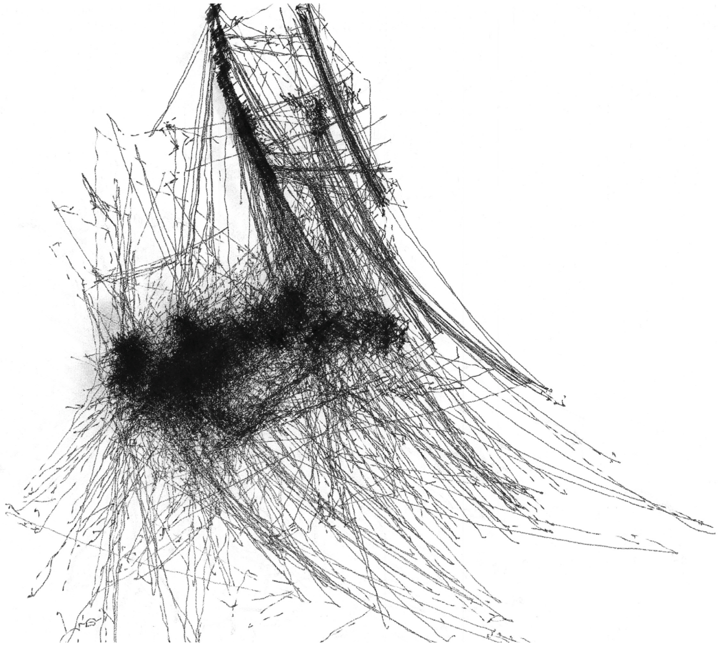

Fig. 2 Output from drawing machine depicting human interaction

5 Connect-The-Dots: Large-Scale Robotic Spatial Generation

Building on the successful completion of the first case study, a series of 3D tests were then initiated. Rather than initially focusing on the creation of physical artifacts as in the first case study, Connect-the-Dots focused on the linkages and processes necessary to directly convert the previously collected human interaction data into controlled, industrial robot motion. In addition to the data collection network established for the first case study, Connect-the-Dots consisted of a four-part system:

1. A Rhino 3D and Grasshopper-based translation system that mapped the data onto a 3D coordinate space.
2. Grasshopper plug-ins Robots.IO and KUKA|prc simulated robot motion and generated control code.
3. A single-board computer (Raspberry Pi) monitored KUKA control program indicators at run time and notified the end-effector of any status changes.
4. A custom, Arduino-based robot end-effector altered the state and color of an LED based on received notifications synced with the robot's movements.

The visualization of the previously collected human interaction data was then translated into 3D motions and visualized through long-exposure photography.

5.1 Translation and Robot Simulation

The algorithm employed to translate color data to 3D coordinates was incredibly simple: red, green and blue (RGB) values were mapped directly to X, Y and Z coordinates and scaled according to the working envelope of the university's KUKA industrial robot arm. The result was a series of 3D points, which were then visualized by connecting the dots in sequence with an interpolated curve.

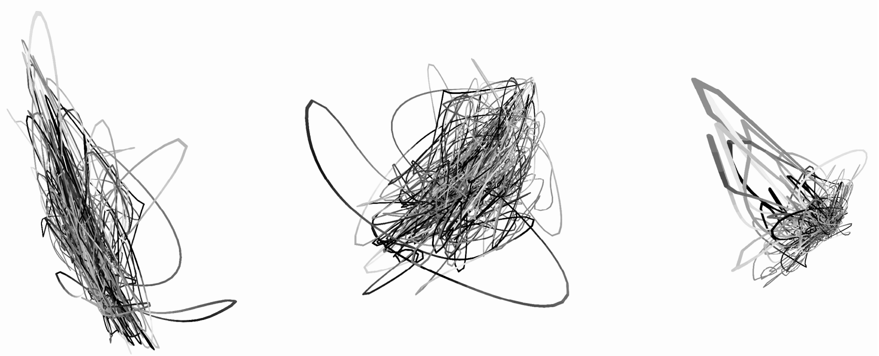

Fig. 3 Simulations of 3Dspatial onstructs created through human data inputs

The Robots.IO Grasshopper plug-in provided the means to simulate and test the viability of the robot motion before any physical test. This involved modeling the robot's working environment, specifying the position of the camera that would be capturing the output, designating the data-generated points as waypoints for the robot and its end-effector, using vectors from the waypoints to the planned camera location to dictate the orientation of the end-effector at each point, and parametrically determining the location of the points in space (as a group) to result in a tool path without singularities or unreachable waypoints.

The simulation process made it clear that new or modified tools are necessary when it comes to the generation of industrial robot motion instructions in the context of a data driven design process, particularly where high precision and repeatability are not required.

5.2 End-Effector and Robotic Output

To render the output of data-generated robotic motion, a simple solution was developed which allowed for the generation of spatial potential through light. A secondary system consisting of a single-board computer (Raspberry Pi) listening to the KUKA controller outputs and an Arduino-based end-effector ran simultaneously during the robot's movement. The Raspberry Pi listened to output signals from the generated robot control code and relayed them via XBee radio to the end-effector that controlled the state (on/off) and color of an LED light mounted to the end of the robot. Through the use of long exposure photography, these controlled lighting motions became traces in 3D space and suggested a potential spatial reality.

Fig. 4 Long exposure spatial output test

The Connect-the-Dots case study allowed for the project's first successful tests in human interaction data-generated, large-scale robotic movements that generated a physical spatial construct (Figure 4). By creating variations in the translation algorithm, any number of variations in form, size and color could now be generated based on minimal amounts of input data and could be used to suggest spaces virtual and/or potential. In addition, like the drawing machine this approach constructs feedback loop. While latency is a factor in its current manifestation (due to the manual steps required between interaction and rendering), the technology exists to explore real-time generation of spatial potentials in response to human interaction [9].

6 Module Maker: Composite Winding End-Effector and Aggregate Module Generation

Whereas the previously discussed data collection and translation systems have demonstrated the potential for the translation of human interaction data sources into both 2D drawn artifacts as well as visually recorded robotic movements, the Module Maker was created to show that these processes could be utilized for the creation orfaddition to the design of large-scale artifacts or spaces, realized through robotic fabrication. A commissioned installation served as the vehicle for developing these processes for 3D artifacts.

As with the first test, this phase of research set up a framework for the production of human interaction data-determined artifacts within certain constraints. These included:

1. The installation would be created using a series of globally unique aggregating modules.
2. Donated 1/8” pre-impregnated carbon fiber tow would be the production material.
3. The module size would be limited by the size of an available on-site oven to be used for the curing process.
4. The end-effector material would be required to have a high melting point and/or combustion temperature.

These constraints led to a unique design solution and opportunities for further research.

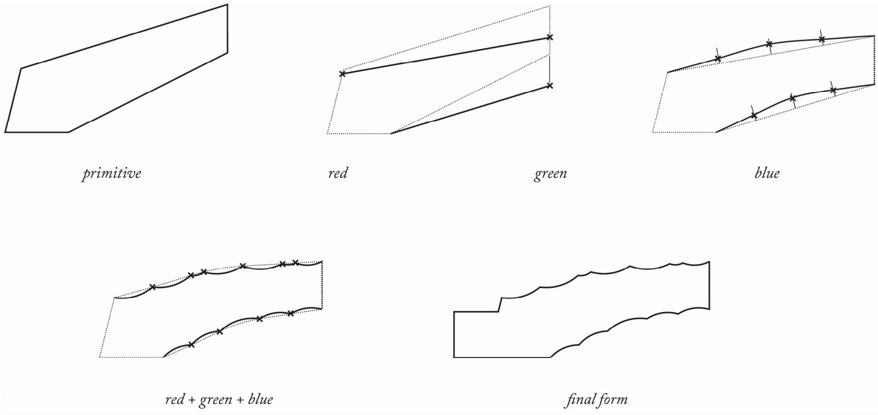

Fig. 5 Translation of color data into end-effector shape

6.1 Translation and End-Effector Generation

This project once again drew on the color data collected using the drawing machine. The translation system was developed using Grasshopper and again made use of RGB values, but instead of mapping to XYZ coordinates, these values were tied to specific parametric elements controlling the angles and inflections of the end-effector edges as illustrated in Figure 5 and superimposed in Figure 6.

Typically significant effort is required in the design and fabrication of unique end-effectors. As the timeline was short for this phase of the project and over one hundred unique modules were necessary, it was imperative to make the fabrication phase as quick and seamless as possible. For this reason and due to the time required for the composite to cure in an oven, cardboard was chosen for the end-effectors. Cardboard could be laser cut quickly using the generated end-effector shape paths, could withstand the 260° F curing temperature, and could be easily removed and recycled once curing was complete. In addition, to minimize the time required in swapping out end-effectors, a laser cut acrylic attachment plate was developed that simultaneously received three separate units and secured them with simple locking mechanisms.

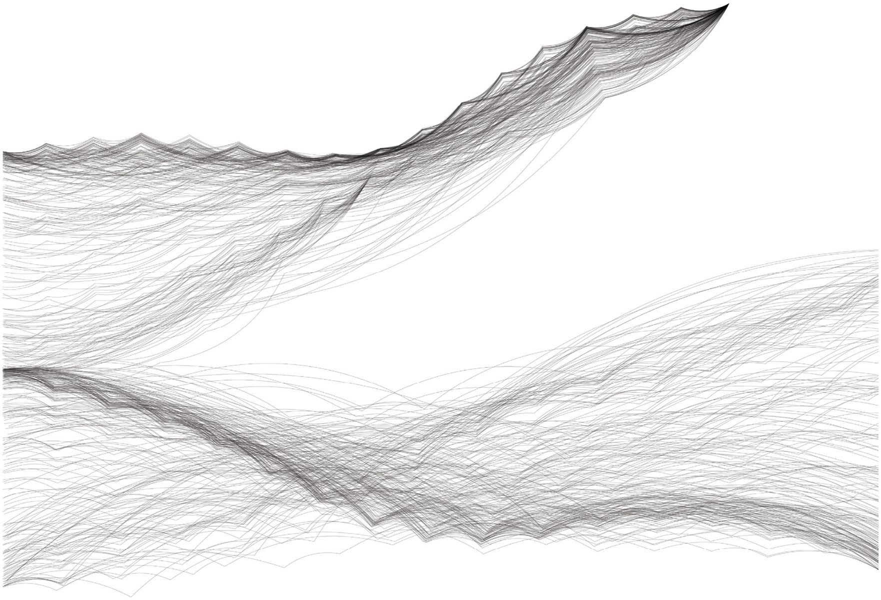

Fig. 6 Human experience-generated end-effector variations

The generated cardboard end-effectors required some assembly once laser cut. Using a numbering and labeling system implemented in Grasshopper and etched into the cardboard during laser cutting, two end-effector shapes were paired for each end-effector and connected through slots in the cardboard with laser cut bridging pieces. These could easily be collapsed after curing to allow the larger side shapes to be extracted with minimal effort. The pre-impregnated carbon fiber tow being used did not closely adhere to the cardboard during curing and as a result the final modules required little to no cleanup.

6.2 Module Creation Through Robotic Winding

Once a few of the end-effectors were cut and assembled the actual winding of the carbon fiber tow around the end-effectors could proceed while more end-effectors were being cut. The winding process incorporated the college's KUKA KR60-3 industrial robot arm with the attached custom end-effectors as well as a stationary tube through which the tow was fed. Due to time constraints and in order to provide a consistent aesthetic, the winding pattern for this exercise was identical for each end-effector, leaving the variation in the end-effectors to allow for the expression of the data. This variation led to varied points of contact between the tow and cardboard while the density of the winding and the degree of intersection was generally consistent.

The methods described for this case study and the previous ones could be applied to other aspects of this design and fabrication solution. It would be possible, for example, to use the data to control parameters related to the winding pattern (and associated robotic movements) for each end-effector, which would reduce the opportunity for error during winding and allow structural concerns to be addressed precisely [8].

Unlike the previous studies, this particular methodology does not lend itself to a real-time feedback loop; however, the result of this process does create the opportunity for a different sort of experience. Like the drawings produced by the drawing machine, there is a mystery related to the form of the modules. They are moments frozen in time and space expressing latent qualities of the initiating interactions. The installation constructed from these modules leverages the latency in this process to both preserve and create human experience.

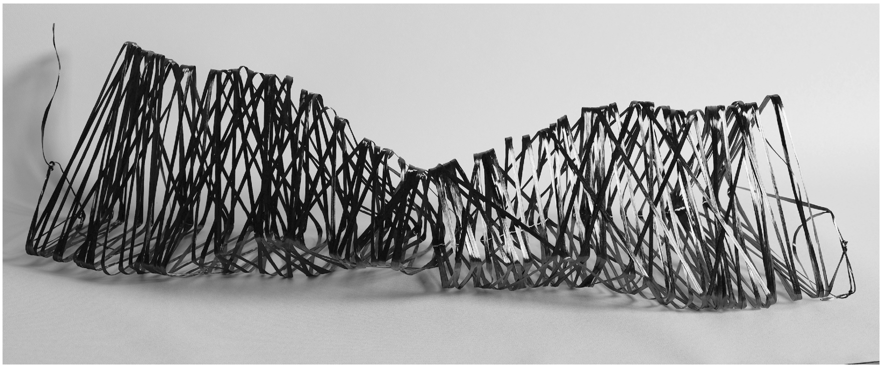

Fig. 7 Two data-driven, wound-composite modules

7 Conclusion

Robotics, including the forms employed in this paper's case studies and beyond, have not only a growing place in architecture, but also in the human experience as technologies develop and become more accessible. Architecture has the opportunity to leverage these new technologies to connect to its users in ways that highlight and value the human experience in the built environment. Although this research is still in its early phases, the case studies in this paper demonstrate the potential of using the data captured by human/robot interaction as a means to create form or as a means to add a level of uniqueness to existing designs. These novel methodologies for translating human interaction data directly into physical artifacts through robotics suggest a means for architects to rethink the initiation and process of design.

The potentials for design found within human experience and interaction are worth further exploration. Continuing this strand of research, forthcoming case studies will examine other forms of human interaction data as well as employing large-scale robotics in real-time interaction.

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