PICA

A Designer Oriented Low-Cost Personal Robotic Fabrication Platform for Sketch Level Prototyping

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Abstract. As digital design and fabrication are becoming increasingly prevalent, it is essential to consider how these technologies can be made more affordable and intuitively introduced to individual designers with limited computing skills. In this paper, we present an affordable personal robotic fabrication platform, PICA, consisting of a 3D printed robotic arm with a set of controller programs. The platform allows designers with limited computational design skills to assemble motors and 3D printed parts easily and to operate it in a code-free environment with direct manipulation through 3D modeling software. With the real-time communication between 3D modeling software and this robotic fabrication platform, PICA also allows designers to efficiently change the topological properties of geometry during the fabrication process. Based on a comparative observation of several application scenarios of using PICA among two groups of architecture students, the research can be summarized as follows: 1.) The project has proved to be an affordable approach to ease the materializing process when converting a designer's initial intent from digital space to a physical prototype. 2.) Designers could be facilitated by utilizing this robotic fabrication platform, especially during the period of conceptual design.

Keywords. Robotic Fabrication; Design and Fabrication; Tool Development; Designer Oriented; Ubiquitous Manufacturing.

1. INTRODUCTION

While the rapid development of digital fabrication tools is expanding the possibility of design space, its complexity reduces the access to the majority of designers who are not equipped with computing skills to take advantage of these technological advancements. Three main contradictions are preventing digital fabrication technologies being more affordable and accessible to designers with limited computational design skills. First, design practice is a process that requires balancing production efficiency and labor input (Arayici et al. 2011). Most of contemporary computational design and fabrication tools hinder their users from mastery by a long-term steep learning curve (Sharma et al. 2011),

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which usually distracts designers from the core content of design tasks to the tool's manipulation (Teng and Johnson 2014). Second, precision and advanced digital fabrication tools are not suitable for the early stages of design that aim to establish the geometric topological relationships of a given design, such as massing study. Digital fabrication tools are mostly expected to be used for final production or late design phases which mainly focus on precise dimensions, positions, and tolerances. However, the physical working model also acts as an intuitive representation during early stages to push a design forward (Knight and Theodora, 2015) in which the precision information is not critical. Utilizing sophisticated fabrication technologies for a physical working model will increase the various costs as well as limit the design possibilities. Third, in the early stage of design, users' demand for consumer-level digital fabrication tools is much higher than industrial-level products. However, consumer-level digital fabrication tools have maintained at a high price, which makes it difficult for independent designers to afford.

Figure 1. PICA, a Designer Oriented Low-Cost Personal Robotic Fabrication Platform.

In this paper, we introduce PICA (Figure 1), a designer oriented low-cost personal robotic fabrication platform that aims to address these sketch-level prototyping issues. This research project is organized at two levels. At the bottom, we aim to develop a reproducible and affordable robotic fabrication platform (including hardware and software) as a foundation, that allows designers to assemble easily and customize upgrades. At the top, by using PICA, we try to design applications that embody direct manipulation with adaptive fabrication processes to aid designers in the conceptual design process. We also aim to liberate designers from complicated machine language coding and operation. We hypothesized that, with a low-cost robotic fabrication system in a coding-free environment, designers with a limited computation background can still conduct a fabrication task to enhance their design experience and smooth the design to fabrication workflow.

2. BACKGROUND

The Design-to-fabrication workflow and increasing popular interest in digital fabrication is frequently obstructed by steep learning curves. Utilizing industrial robots for fabrication demands two learning subjects. On the one hand, robotics is an enormous interdisciplinary subject. Designers and researchers should have essential exposure to various topics, including mechanical design, kinematics, end-effector design, machine language coding, spatial analysis, and sensing technologies (Shahmiri and Ficca 2016). On the other hand, the operation of robots is also equivalently essential. It is worth pointing out that most industrial robots are painted with orange, it indicates that operating an industrial robot is usually restricted and dangerous (Edgar 2008). Learning the robot operation protocol is often time-consuming for beginners ,and getting familiar with the manufacturing procedure and material property also requires designers' input. All the expertise which most designers were not supposed to be equipped with in their career path demands a considerable investment of time and energy.

Second, the architectural design process reflects the designers' imaginative ideas and their materialization procedure. The thinking pattern beneath this process is a transition from abstract to concrete, and flexible to restricted. The majority of contemporary digital fabrication tools are numerically driven, which requires the users to input the precise numbers, even when their design ideas are in the early stage. The precise number is not capable of handling uncertainty, multidimensional complexity, and flexible compromises. Quite the opposite, excellent design inspiration, also known as the ”aha moment”, is often generated in a relationship-oriented adaptive environment rather than in an accuracy driven setting.

In addition, since design is an iterative process, the repetitive work is unavoidable (Simon 1996, Meng 2009). One of the main goals of the repetitive work is to seize and optimize these reiterative insights and inspirations through continuous trials and errors, then push the design concept to the implementation at a more practical stage. The working model plays a critical mediating role in the design process, it is not only a representation and summary of design outcomes but that the tactile and material engagement helps to explore and discover the hidden design potentials (Knight and Theodora 2015). Utilizing robotic fabrication technology to make a working model is not ideal. For instance, to make a model for a massing study by a robotic arm, the designer firstly needs to determinate an exact size of the massing, then set up a toolpath by scripting in the robot controller software. After the robot slowly processes the model, the designer might find a particular size needs modifying, so the designer has to repeat the previous operation until the result is satisfied. Existing robotic fabrication processes are complicated and non-intuitive. Precisely sized geometry is converted–which is likely modified in later phases–to readable machine language and further translated to sophisticated equipment. The designer-oriented fabrication process needs to be more intuitive to encourage designers to focus more on the overall geometric form instead of a specific size. Meanwhile, the robot needs to be controlled in real-time rather than in a one-way execution to take advantage of uncertainty to generate new inspiration. In short, the model should be rapidly made with a more user-friendly means.

The argument above is not to deny the importance of precision fabrication in the later design phases, however, considering the cost of robotic fabrication, it is unnecessary and uneconomical to utilize an industrial robot in the early stages, such as with a massing study. A piece of low-cost consumer-level equipment is sufficiently functional to perform most of the fabrication task.

3. RELATED WORK

The establishment of our project PICA starts from the investigation of direct manipulation and live control of a robot as well as the prototyping process in terms of design. Recently, research has been developed and conducted to operate an industrial robot through an operator's direct behaviors without working in software user interface and to conduct fabrication work. For instance, Andrew Payne (2011) developed a robotic motion controller with 5DOF that can be manually operated by users. The potentiometer reads the rotation angles and sends to an ABB industrial robot. But the controller can't make the industrial robot follow a pre-defined toolpath since the robot is controlled through forward kinematics, and thus restricted the application of this direct manipulator in fabrication tasks. RoMA (Peng et al. 2018), combines robotic fabrication and augmented reality in the same volume to allow the designer to build a model in an AR environment; the robotic arm follows the designer's gesture to print a wireframe model in real-time. FormFab (Mueller et al. 2018) develops a formative fabrication method that changes a closed thermoplastic shape by warming specific areas to adjust internal air pressure. Users' gestures determine where the thermoplastic should be warmed up by the heat gun attached to a robotic arm.

There are other existing research projects explore real-time control of the robotic arm for fabrication. The popular software that has the potential to connect both 3D modeling activity and robot operation is Grasshopper. However, sending real-time data to robot operation software from Grasshopper often requires multiple layers. Some of the famous example that can control robots via Grasshopper are HAL or KUKA. However, the fact is that this program is designed to generate the toolpath and convert the toolpath into robot programming languages such as RAPID and KUKA, which means that operators still need to execute toolpath commands through robot controller software. Besides sending real-time data to change an executing program, some of the research showcases opportunities for sending real-time data to control an end effector, which typically runs as a stand-alone device. Robosense (Rosenwasser and Sabin 2018) is a project that attaches sensors to the robot's end-effector. It uses these sensors to monitor environmental and material factors, then applies these parameters to change the extruding pressure.

4. IMPLEMENTATION

4.1. HARDWARE IMPLEMENTATION

The making of PICA starts from an in-depth investigation of the current 6DOF industrial robotic arm and designers' demand for personal fabrication. To design a new configuration of a robotic arm, we firstly determine the constant motion and structure parameters of the robot, including the maximum movement speed of each axis according to the duration required to complete the task. Hereafter, with the assistance of a robot's parametric kinetics model that we build in Grasshopper, we determine the length of the upper arm and forearm based on the maximum motion range that is capable of carrying the allowable payload to the end effector.

The core components of PICA include the main body, motors, reducer, and controller. The fully 3D printed main body of the robot arm is sufficiently robust for lifting tasks. The main body, similar to industrial robotic arms, is assembled by a base, shoulder, upper arm, forearm, wrist, and a series of grippers. (Figure 1).

Since the primary users of the robot arm are designers, we accomplish a parametric digital model of PICA with Rhinoceros & Grasshopper and make a set of customized components in Grasshopper to control the assembled robot arm directly, which gives easier access to designers and offers opportunities for further development. Since PICA follows the model of "joint-link-joint-link-...-link-end effector," (Figure 2) the parametric model of the robot is mainly determined by the length of links. It establishes the overall relationship between various parts, and defines the size, shape, and position of each component in the entire configuration. In the future, when a designer needs a new robot arm to perform a new fabrication task which requires a broader moving range, he or she can achieve it by setting a new length of arm segment and printing the new replacement (Figure 2). Also, the control signals are updated with the kinetic model accordingly in the Grasshopper definition.

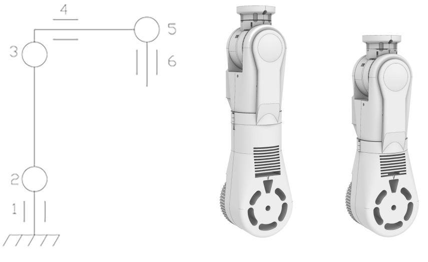


Figure 2. joint-link-joint-link-...- link-end effector model (Left) and the two forearms with different length generated by the parametric model (Right).

Generally, for ensuring precision of movement of the robot arm, servo motors are used in the heavy-duty industrial robot arms. The motor encoder of the closed loop drive system is used to achieve high precision movement. However, as this project aims to develop a lower cost configuration with relatively acceptable accuracy control, seven bipolar stepper motors are used instead of servo motors. According to the configuration of the axes, all six axes can be classified as two types based on its stress situation, every kind of axes have similar calculations. For the axis of 6,4, and 1, it overcomes the inertia force and friction force since the 3D printed parts on these axes are engaging each other. Axis of 5, 3, and 2 is another type that is primarily rotating against inertial forces, friction, plus gravity. Therefore, the calculations of axis 5, 3, and 2 need to consider the impact of gravity. After determining the necessary load and transmission, the primary motor parameters such as holding torque and the rated current can be calculated based on a complete rotation range of the joint. The calculation above helps to determine the stepper motors. In this project, the stepper motor types that are used in PICA are NEMA 23, NEMA 17, and NEMA 14.

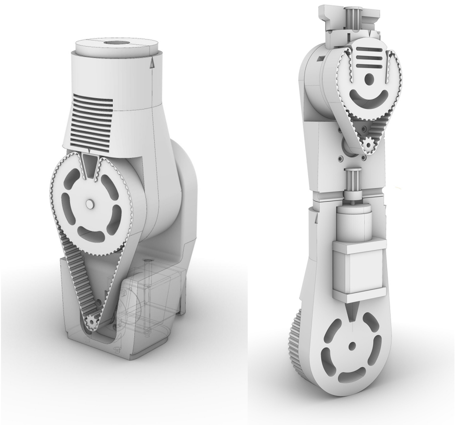


Figure 3. Two types of the joint system: Left, Axis of 5, 3, and 2; Right, Axis of 6,4, and 1.

In terms of the reducer, harmonic drives and Cycloidal drives are commonly used in the industrial robot, which decelerates the motor rotation and increases torque. Deceleration ratio and I/O torque are considered when selecting the reducer. The deceleration ratio of each axis' reducer is determined according to the relationship between the maximum speed of the motor and the required motion speed. For motors that directly connect with the reducer, the maximum reduction ratio can be directly obtained. Moreover, for the motor that connects with the reducer through transmission, it is necessary to determine the maximum reduction ratio according to the design of the transmission and motor speed. In our configuration, for economic considerations, we design a joint system that uses a timing belt to achieve the same purpose of the reducer (Figure 3). Stepper motors at 1,2,3 and 5 axes use this timing belt system to drive remaining joints after the reducer decelerates and amplifies the torque. However, for the 4th axis, as the forearm is very compact, we retain the stepper motor with harmonic reducer as the transmission device.

We also successfully achieve one of our goals as we are aiming to establish a new configuration of a 6DOF robot arm with lower cost comparing with an industrial robot arm. The total cost of PICA, including all necessary components, is less than $800 (table1), making the robot arm affordable for most designers.

4.2. SOFTWARE AND CONTROL

As mentioned above, PICA is a designer-oriented robotic fabrication platform It is developed via a parametric model in Grasshopper that allows designers to define the different lengths of arm segments. Meanwhile, PICA also is operated via Rhinoceros with Grasshopper. A set of customized grasshopper components is made for completing the operation. Fundamentally, there are two approaches to control the robot, and one way is sending rotation degrees on each joint and driving the robot by inputting a number a number directly. This approach is mainly used for moving the robot arm without an expected toolpath. However, since we are conducting a designer-oriented robotic fabrication platform, the robot is required to track toolpaths in most cases. As such, inverse kinematics analysis is significant in the project. The inverse kinematic analysis Grasshopper component allows real-time computer calculations of the rotation degree at each joint. This is based on the position and orientation of the robot's end effector in the spherical coordinate system by applying Denavit-Hartenberg parameters. We set six individual coordination systems along each joint, defining the axis as Z direction and common normal (the link between two joints) as X direction (Figure 4).

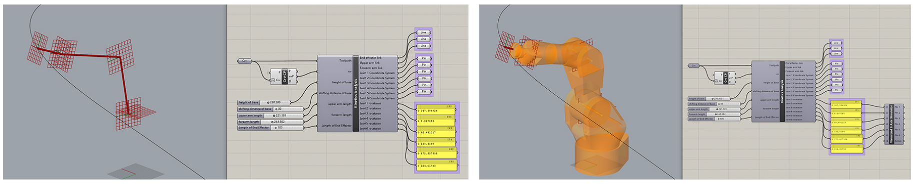


Figure 4. The Kinematics Analysis Component calculating rotation angle and coordination system on each axis, with the input of length of each link and end effector (left) . The filtered solution of inverse kinematic analysis with a visualized robot simulator(right). .

In terms of inverse kinematics calculation, the first step requires obtaining the coordinates and the position of the end effector and to then determine whether the coordinate is in the working range of the arm, and if it is, the inverse kinematic calculation starts. Next, divide the six joints into two groups. First, use the descriptive geometry method to calculate joints 1, 2, and 3. Since the calculation of these three joints are separated from joints 4, 5, and 6, together, they hold the overall posture and positioning of the robot arm. Joint 1 mainly controls the rotation of the whole arm and can be projected to the XY plane for calculation. Joint 2 and joint 3 are separated from the overall rotation of the robot arm and can be projected to the XZ plane or YZ plane for calculation. After completing the calculation of joint 1, 2, and 3, the results are substituted into the D-H matrix of the robot arm to prepare for subsequent calculations.

As most fabrication tasks require a toolpath, which is a 3D curve in digital space, the topological property of this 3D curve as well as the shape of the end effector will define the rotation angle of the rest of the joints. For instance, when conducting a milling task, the direction of the end effector will need to be perpendicular with the tangent vector of the curve at a specific point. This direction, along with the end effector length, determinates joint 4 and 5. According to the constraint conditions, it obtained multiple solutions of arm's posture. We filtered these solutions that are not satisfied with the constraint and select the optimal solution as the final result according to the shortest path principle (Figure 4).

4.3. COMMUNICATION BETWEEN COMPUTER AND PICA

PICA connects with an Arduino Mega board as media to receive data. The host computer generates all joint rotation angles via grasshopper inverse kinematics components. These generated angles need to convert into step numbers to be sent to stepper motors through Arduino to get the robot working. A set of stepper motor drivers (TB6600 in this case) is associated with each stepper motor, which send step and direction information and provide sufficient rated current.

In terms of the communication method between the host computer and Arduino, through case studies, we found that most designers are using Firefly to connect Arduino with a computer. Firefly, as an excellent example of a visual programming tool, provides a more comfortable and intuitive way for designers to operate Arduino and build simple interactive prototypes. However, it is not the best option for us since we are eager to motivate designers to be less dependent on design tool manipulation in order to focus on the design process with the help of PICA. Firefly has a number of limitations. The maximum number of stepper motors is only four, which is not capable of carrying what we need. In addition, we need to save digital pins for end effector development. In this project, we attached an ethernet shield with Arduino Mega board to convert it as a standalone client with an IP address. By locating this IP address with UDP in Grasshopper, all data for 6 or more stepper motors can be sent to Arduino as a string through the ethernet cable (no USB connection required). As such, if the designer needs to further develop an end effector to perform a fabrication task, he or she can have a separate Arduino board connecting with host computer via USB.

Our configuration of PICA allows real-time communication between the robot and host computer. This is because PICA does not have to be operated based on robot programming languages. Grasshopper is capable of streaming data over UDP, but the inverse kinematic analysis software doesn't have to be limited within Grasshopper, as long as the software supports UDP. This streaming approach adds media to help those designers who have limited expertise in robot programming language.

5. APPLICATION of PICA

The design of the end effector primarily determines the Application of PICA. In this case, we aim to examine if direct manipulation and real-time control can facilitate modeling activity at the sketch level to reflect the vision of this research. Firstly, we attached a modified hot glue gun on axis 6 as PICA's end effector and paired it with the other stepper motor to extrude the hot glue filament. Additionally, we also set up a pottery station that allows participants to throw clay on a turntable, and to be scanned by two IR depth scanning device.

The goal is to extract spatial and formal data from real-time analysis of a designer or artist throwing clay on a wheel and to then use these data to shape any form of vase directly by a person's hands. The two IR scanners capture the shape-changing process of this vase from a rough massing to a decent ware. Meanwhile, the dynamic shape is digitized into the Rhinoceros interface in real-time and the PICA plug-in is used to generate a toolpath that wraps around the digitized mesh. As data is captured in real time, PICA starts printing another vase in hot glue following the bespoke changing shape of the clay vase that is being manipulated by the designer or artist. As the printing material is hot-melt adhesive, it offers us the opportunity to change its shape when maintaining a high temperature. While the designer modifies the original clay object directly by his or her hands, the printed geometry is also modified by the robotic arm with its hot end as it is slowly pushing and dragging the vase wall. Since the hot glue sticks have a larger diameter than regular filament, precision is lost. We are still exploring methods to cool down the printed material faster. However, this interactive robotic fabrication process confirms our argument that a low-cost robotic system is capable of conducting a sketch-level modeling task through direct manipulation and real-time control. (Figure 5 and 6)

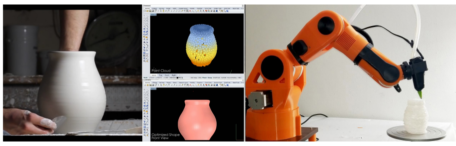


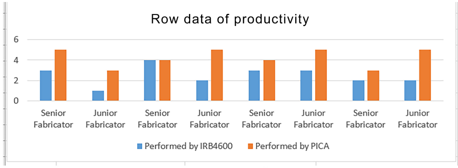
Figure 5. IR scanners are recording the throwing process performed by a designer; Rhino/Grasshopper generates an optimized shape and toolpath for robotic printing, and A tangible vase printed by PICA with hot-melt adhesive.

Figure 6. Vases printed by PICA.

Based on this application, we designed an experiment to evaluate our hypotheses. The experiment was performed in an academic design environment and research lab. The first independent variable is the robot that all participants used to print a vase, whether the use of PICA or an industrial robot (IRB 4600, in this case). The second independent variable is the digital fabrication experience that all participants engaged in. The dependent variable is the productivity that participants had during the study. The techniques that each participant deployed to make a vase is within-subject factors and fabrication experience as the between-subject factor. Participants were from the architecture department at Cornell University. All 8 participants varied with pre-experience and grade; designers with no more than one year experience of digital fabrication were marked as junior fabricators, and the rest are marked as senior fabricators. All 8 participants were familiar with 3D modeling software Rhinoceros to be used in the experiment at different levels.

First, participants were randomly assigned a picture of a vase and were asked to make the clay vase massing by hand according to the picture and to simultaneously 3D print it with PICA within 15 min at the same time. Second, they were randomly assigned a different picture of another vase and were asked to build a 3D massing in Rhinoceros according to the picture and to 3D print the vase with the IRB 4600 (2mm extrude mounted) within 15 min. The dependent variable, productivity, was measured by the completed portion of the vase, printed either by PICA or the IRB 4600. The qualified vase massings should be similar or the same as the picture provided in the experiment. Successfully printing the entire vase would be scored 5, completed printing 80% (measured by finished height) of the vase would be score 4, and so on. After the experiment was complete, the raw data was collected as follows. (Table 1)

Table 1. The raw data collected through the experiment (up) and the Effector of the fabrication method with different experiences on the productivity test score (down).



Averaged Test Score

	Performed by IRB4600	Performed by PICA	Mean
Junior Fabricator	2	4.75	3.375
Senior Fabricator	3	4	3.5
Mean	2.5	4.375	

The results are indicated as follows, a 2 X 2 (fabrication method X digital fabrication experience) factorial analysis of variables (see Table 1). The dichotomous data (low-cost robot arm or industrial robot arm) resulted in highly significant results. As shown in Table 2 and 3, the participants assigned to use the industrial robot for the printing task in the group of junior fabricators reported an average score of 2 on the productivity measure. Meanwhile, an average score of 4.75 was reported when a junior fabricator group printed with PICA with direct manipulation. Participants assigned to use the industrial robot for the printing task in the group of senior fabricators scored an average of 3, and an average of 4 in the printing task with PICA along with direct manipulation. The mean score varied from 2 to 4.75 across the four scenarios. The results suggest that productivity is impacted significantly based on the fabrication method. The average productivity for both groups improved. The productivity measured by PICA (associated with direct manipulation) is significantly higher in comparison to the productivity measured by IRB 4600 (associated with the regular one-way fabrication workflow). The productivity of PICA & direct manipulation approach (mean=4.375) is greater than that of IRB4600 regular one-way fabrication workflow (mean =2.5). The level of a designer's digital fabrication experience also impacts productivity. Generally speaking, designers who have more working experience have higher productivity. The productivity measured in the senior fabricator group (mean= 3.5) is greater than the junior group (mean=3.375).

6. CONCLUSION

The research project PICA provides a practical approach for designers with limited computational design experience to conduct fabrication tasks via a low-cost robotic platform. Designers could benefit from utilizing the described platform, especially during early phases of the architectural design process. PICA allows designers to focus on the topological properties of massing and to fabricate it with a user-friendly interface. Meanwhile, we encourage designers without computing skills, the target group of this project, to build their low-cost robotic platform for personal fabrication by replicating our design. Last but not the least, the realm of designer-oriented low-cost robotic fabrication tool remains partially unexplored. This research sits at the intersection of architecture and Human-Machine interaction, but does not necessarily solely reside in either. Instead, the work we propose resides at the interconnection between multiple areas - an interdisciplinary and collaborative environment is a necessary condition to support further research.

References

Arayici, Y.: 2011, Technology adoption in the BIM implementation for lean architectural practice, *Automation in Construction*, **20**(2), 189-195.

Bilotti, J.: 2018, Robosense 2.0. Robotic sensing and architectural ceramic fabrication, *Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture*, 276-285.

Edgar, B.L. 2008, A Short Biography of KR150 L110, *in* F. Gramazio (ed.), *Digital Materiality in Architecture*, Lars Müller Publishers.

Meng, J. C. S.: 2009, Donald Schön, Herbert Simon and the sciences of the artificial, *Design Studies*, **30**(1), 60-68..

Mueller, S.: 2019, FormFab: Continuous Interactive Fabrication, *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*, 315-323.

Peng, H.: 2018, RoMA: Interactive fabrication with augmented reality and a robotic 3D printer, *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 579.

Rosenwasser, D.: 2017, Clay Non-Wovens: Robotic Fabrication and Digital Ceramics, *Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture*, 502- 511.

Sharma, A.: 2011, MozArt: a multimodal interface for conceptual 3D modeling, *Proceedings of the 13th international conference on multimodal interfaces*, 307-310.

Simon, H.: 1996, *The Sciences of the Artificial*, MIT Press, Cambridge.

Teng, T.: 2014, Inspire: Integrated spatial gesture-based direct 3D modeling and display, *Proceeding of 34th Annual Conference of the Association for Computer Aided Design in Architecture*, 445-452.

Terry, K.: 2015, Computational Making, *Design Studies*, **41**, 1-7.