Beyond Digital Steroids: A Pedagogical Approach to Foundation Design Education Through Design Robotics

A case study in kiln cast glass using a Processing-based analogue design-to-robotic fabrication workflow in the Spatial Dynamics Studio at Rhode Island-School of Design.

NATHAN KING
Harvard University, Rhode Island School of Design, and Virginia Tech

JONATHAN GRINHAM
Harvard University

STEFANIE PENDER
Rhode Island School of Design

RACHEL VROMAN
Harvard University

CHIP CLARK
Virginia Tech

INTRODUCTION: A PEDAGOGICAL POSITION

Foundation Education in Spatial Dynamics

The general practice of fundamental design education, particularly three-dimensional spatial dynamics, for students ranging from 17-19 years of age has struggled with the incorporation of digital design and fabrication technology. In many cases the introduction of the 'digital' into early design curricula is met with resistance, if not set at odds, with well-established pedagogical constructs that develop material understandings of action and result, through physical iterative processes. That resistance to non-physical simulated interfaces may be warranted, but it should not be so quickly applied to digital output tools of material-processing technologies. Those technologies are being inaccurately aligned and perceived as dependent upon virtual design environments. The intention of the following studio efforts is to challenge these associations and bring to light the potential for digital fabrication tools to serve as mechanisms that enable students to develop modes of practice that fosters rigorous critical thinking and informed action within the foundation design curriculum.

The Foundation Design Studio Environments

Foundation-level design studios with pedagogical frameworks that prioritize learning through making and the pursuit of individual goals and objectives are conducted in the Virginia Tech School of Architecture + Design and the Rhode Island School of Design. In both studio/laboratories students engage in the physical creation of works that are relevant in a larger context while investigating their own questions relating to expression, process, intention, and invention. Through active participation in a series of assignments, discussion, workshops, lectures, and readings, students are exposed to a range of concepts both applied and theoretical. In these courses students utilize a number of tools to manipulate a variety of materials and making plays a critical role in the curriculum.

Within this context, digital tools are often ignored or used in parallel to support a primary investigation and in many cases are viewed as specialty technologies that are perceived as a ‘black box’ or means-to-an-end, rather than a fundamental design tool capable of informing the development of a well-rounded design sensibility. This perception is exacerbated by the digital interface and modeling platforms that, at the foundation level, offer no connection to material behavior and completely lack the feedback necessary to critically evaluate design decisions outside of the virtual environment, thus are incapable of informing physical perceptions. It is popularly accepted in academia that three-dimensional digital interface can lead to decisions, or rather uninformed actions, made in haste, resulting in the transformation of loose ideas into virtual representations of things and stuff at an accelerated rate; where as, at the foundation level a fundamental tactile experience is necessary to understand the world and the consequences of our actions within it. From this perspective, the authors are in agreement with the notion of Digital Steroids posited by Professor Scott Poole while director of the Virginia Tech School of Architecture + Design that suggests that;

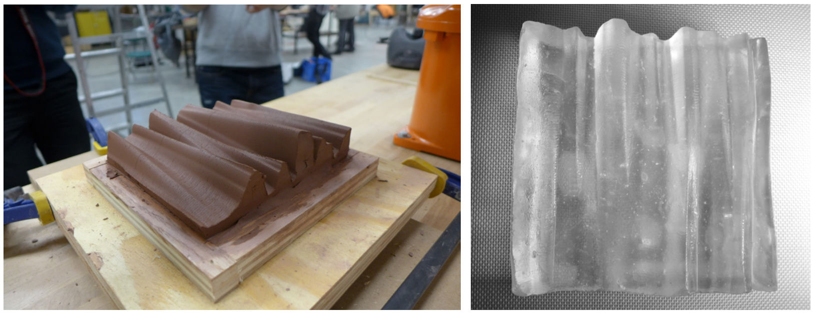
> “The urgent task of the teacher is to put students in a position to grasp this secret bond between slowness and memory, between long attention and lasting impression, before they become seduced by the general euphoria of virtual reality, promises of enhanced velocity, and illusions of automatic virtuosity.”(Poole 2003)

Design Robotics in the Academy

Separate from other digital fabrication tools, CNC Milling machines, and 3D printers, the six-axis robotic manipulator, once removed from the virtual representation environment, offers a unique opportunity to develop spatial sensibilities and critical thinking ability through an understanding of machine-material interface, complex movements in space, and the resulting physical actions. For many, the industrial robot is analogous to the digital and therefore should be isolated at the advanced levels, if at all, within design education. Design Robotics, as defined by the Design Robotics Group at the Harvard Graduate School of Design positions the robot to advance design research and pedagogy (Bechthold 2012). In some cases this work is fueled by perceived robotic potential and in others the machine is simply in service to a larger research question, as a direct process proposition or a simulated manufacturing environment. In all cases strategic robotic engagement is considered within a rigorously evaluated material system. As technology evolves, this rapidly changing field continually presents architects and designers with new challenges and opportunities. At the graduate level, courses surrounding design robotics ultimately pursue questions of design, positioning and testing technology as a driver in creative design processes, while providing an outlet for critical evaluation. Even in this advanced context the robot is relegated to an isolated environment, utilized by a very small percentage of students, and is rarely treated as a fundamental design tool capable of informing the development of core design intuition and critical thinking abilities.

Workflows in Action

Prior to the development of design-to-robotic fabrication workflows, robotic programming was shrouded in mystery within isolated proprietary industrial systems that resulted in a steep-specialized learning curve that further isolated the machine from mainstream curriculum. The introduction of automated tools that link many three dimensional modeling environments like Grasshopper for



1

Rhinoceros, Catia, Maya, etc to robot code generation enabled a rapid uptake in robotic activity within design schools and to a lesser extent in the related professions. For example, the 2011 Smart Geometry workshop Ceramics 2.0, utilized a combination of two Rhinoceros-based code generation tools, HAL and DRGPRG, to create a direct link from Rhino-to-robot that enabled a group of 13 students to engage robotic material manipulation immediately following a basic tutorial. In this case students began with a series of hands-on exercises that enabled a material and process understanding relative to the prescribed automated workflow by engaging in analogous manual material and process experimentation. This is not to say that students become expert robot operators, but that they acquire the minimum knowledge needed to begin to engage the machine. For these students the transfer from the digital to the robot was predicated on a relatively high understanding of the Rhinoceros modeling environment and some level of experience actually doing 'things' with materials.

The influence of automated digital workflows is realized in the sheer number of industrial robots acquired by design schools in the past few years. Additionally, multi-move controllers and related automated workflows have enabled collaborative robotic work cells to enter the scene and laboratories like the ones at University of Michigan, Taubman College Digital Fab Lab and The University of Innsbruck's REX Lab which have be highly successful in advancing opportunities for multiple Robots in Architecture, Art, and Design. While the incorporation of industrial robots is an exciting prospect for the advancement of design and the realization of new opportunities for Making, the limitation of these activities within a Foundation design curriculum is in fact the digital interface and, as stated by Professor Poole in the his treatise on Digital Steroids:

"While three dimensional software programs and rapid prototyping devices produce remarkable shapes, those shapes have less to do with finding limits, an essential aspect of art, architecture and design, than working within the pre-established limits of the software not the designers imagination." (Poole 2003)

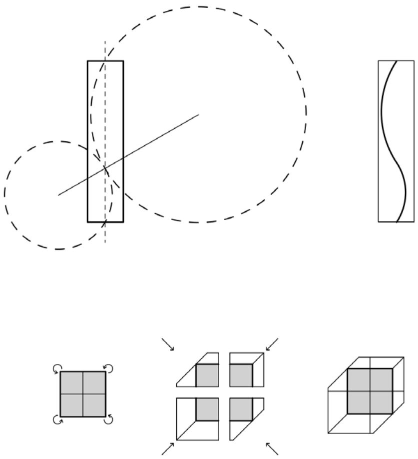
Durable Knowledge

While there is no substitute for "making and depicting a physical object by hand" the industrial robotic manipulator does offer the potential to create the durable knowledge called for as an argument against 'Digital Steroid Abuse' that "involves changes in perception and a specific awareness of facts that one arrives at through intense observation and constructive effort. " (Poole 2003)

This paper contextualizes the industrial robot through an expansion of a long-standing foundation design exercise developed by the Center for Design Research at Virginia Tech and through an analogue design-to-robotic fabrication workflow, positions the machine firmly in the context of foundation design curriculum as a design tool capable of producing durable knowledge and informing a rigorous

Figure 1: Robotically cut clay pattern and resulting cast glass part.

understand of design through highly considered automated material manipulation resulting in a series of kiln-cast glass artifacts.



2

STRATEGIC STUDENT DESIGN EXPERIMENTS

Design a Line as a Tool Path for the Band Saw

This exercise, developed by the Virginia Tech Center for Design Research, is common in the Foundation Design Laboratory and is used as a springboard for launching new students into the process of Design Research and Evaluation. The exercise begins with the designed geometric construction of a line that begins and ends at the midpoint on the short lengths of a 4” x 18” rectangle at full scale in graphite/ink. The line may not touch any part of the rectangle otherwise, nor can it touch itself. This drawing is then presented to and discussed by the studio. The next phase of the exercise is then revealed: the student must reproduce their designed line on two equal adjacent faces of a 4” x 4” x 18” stock of a suitable material to be passed through a bandsaw. The student cuts each line using the bandsaw: after the first cut, the material is rejoined with masking tape, rotated 90 degrees so the adjacent face can be passed through the bandsaw again. The student must faithfully trace their designed line with the blade, and if the operation cannot be completed due to incompatibilities between designed line, bandsaw, and material, the student redesigns the line to account for the limitations of the bandsaw and the stock material. Limitations are particularly evident when students prescribe tight radii that exceed the capacity of a given blade dimension, a correlation that will arise in the robot workflow described below. Finally each piece is freed from the volume and rotated 180 degrees around its long axis so that the original external corners now occupy the center.

Aside from the material lost to the kerf of the cutting blade, the volume and mass of the 4x4 is preserved, its form and spatial presence, however, are drastically altered. A section cut anywhere along the 18” axis and parallel to the 4x4 plane reveals a true 4x4 regardless of the designed line. What comes to bare are the limitations of the tooling in relation to the nature of the intended line. Straight cuts and tangential curves are within the tool’s scope, but multiple sharp faceted lines and angles cannot be accomplished within a single continuous pass, despite the ease in drawing them. Once material and process is applied to the line resistance become tangible leading to line deviation, material burning, and/or blade breakage. This process creates a healthy iterative feedback loop for foundation students as they evaluate results against intentions and successive iterations against their predecessors.

3

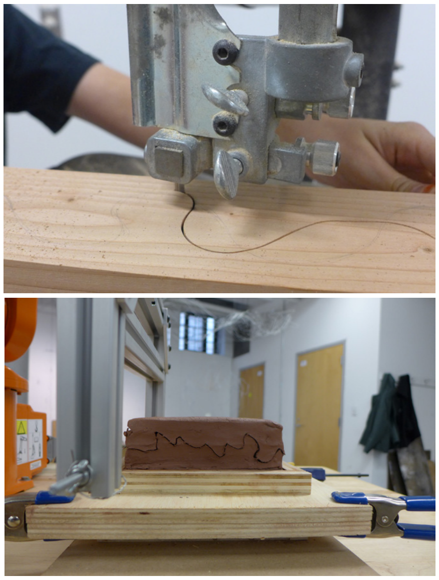
Figure 2: Diagram of 4x4 and Line exercise showing two tool paths and resulting geometry.

Figure 3: Physical results of reassembled band saw parts. Each cross section remains 4”x4” despite formal complexity.

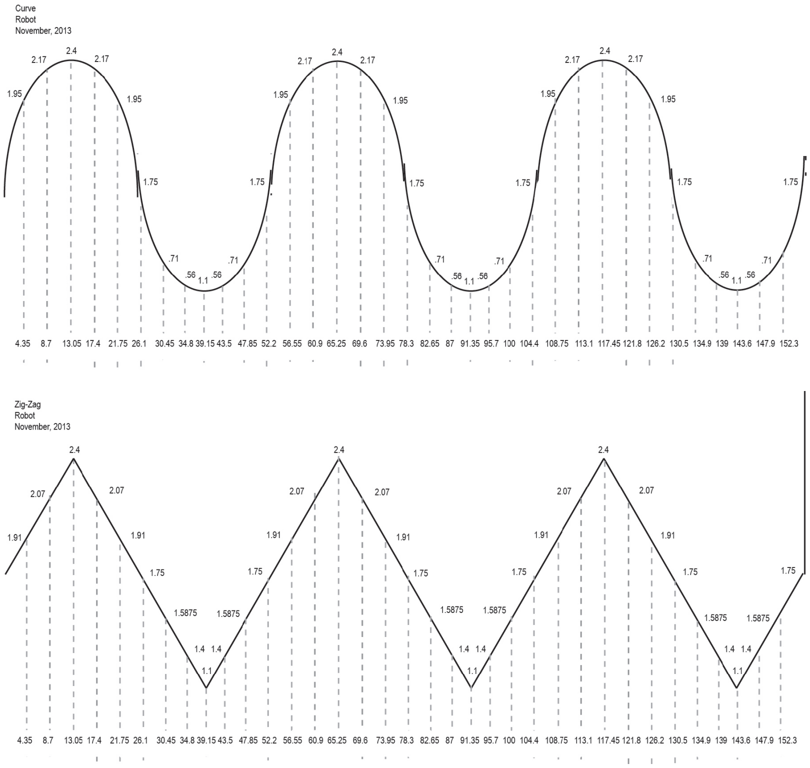
Analogous Robotic Process

The exercise described above has a parallel in a common robotic process- wire cutting. Robotic wire cutting has been used in a number of projects and a variety of materials. In this case the material exercise extends from wire cutting research began by the Harvard Graduate School of Design during research into opportunities for variable ceramic extrusion through industrial robotic integration (Andreani 2012). Much like the bandsaw blade, the wire has certain limitations that, when exceeded, result in a deviation from the prescribed line. The minimum radius of the bandsaw has a corollary in the zone data within the robot code the deviation from a prescribed target effectively gives the interpolated path a minimum radius.

While diagrammatically similar, the robotic wire cutting process exhibits its own unique tooling parameters and considerations. The tracking of the wire, when under excessive pressure due to elevated move velocity or sharp directional change, bends under tension resulting in a deviation from a prescribed line. In most processes deviation from the prescribed (inaccuracy) is undesirable. Within the context of the Foundation Laboratory deviation is representative of physical material realities and it is and understanding of this behavior that feeds the iterative cycle to begin to address the relationship of the ideal geometry (the designed) and the realized geometry (the made). With this process the feed back from making is present within the digital fabrication process.



4



5

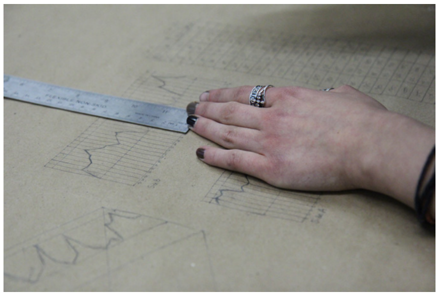
Figure 4: Comparison of band saw-cut line and robotic wire cut line. Radial deviation can be seen in both examples.

Figure 5: An example of a pair of measured lines, represented digitally, that provides the inputs for the Processing workflow by way of ubiquitous Google Spreadsheet (Student work: Phoebe Morrison, RISD Spatial Dynamics Fall 2013).

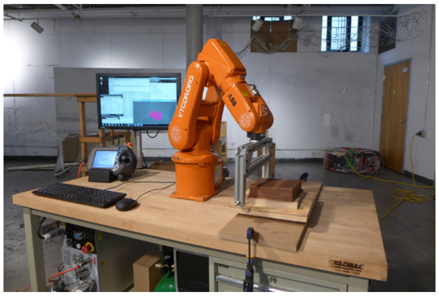
Design Two Lines that Create Robotic Toolpath

A parallel exercise was developed that incorporates the pedagogical construct from the first bandsaw-based project yet introduces addition levels of material interaction and in this case the primary material manipulation is in fact a tooling process. The assignment is simple, design 2 lines within a strict set of parameters.

6



7



In this case students were asked to develop an isometric drawing of a bounding box to represent a stock clay block. In the drawing, two parallel faces can be used to predict a ruled surface from 2 measurable lines. The dimensions of the block (6” x6” x2”) correspond to metric measurements that lock the y coordinate of each face at 0 and 154.2mm so coordinates x and z can be measured from the line drawing. Working between 2 elevation drawings and the isometric projections students develop a pair of lines and corresponding ruled surface. Additional parameters are assigned based on the corresponding material process. The robot-cut clay part is used to create a plaster-silica mold that can be used in the glass casting process, which means a minimum sharpness, and limited undercuts are desired. Again, the lines cannot intersect themselves.

Once designed, the two lines (rails) are defined by a series of points. The more points applied to the line, the higher the fidelity of the eventual robotic cutting. The number and location of points is up to the designer with the exception of two parameters. First, the number of points on line A must be the same as line B and there must be a point at the end of each line. The location of each point is measured and the coordinates entered into the spreadsheet-based robotic programming interface described below.

ANALOGUE DESIGN-TO-ROBOTIC FABRICATION WORKFLOW

Robotic Work Cell

To enable the incorporation of the industrial robotic manipulator in foundation laboratory exercises an industrial robotic ‘teaching’ cell, based on the ABB IRB-120 robotic manipulator was developed by the Virginia Tech Center for Design Research and placed on loan to the Rhode Island School of Design Division of Foundation Studies for this study. The IRB-120 offered by ABB to educational institutions is a relatively low-cost entry into the field of industrial robotics and offers a flexible platform that requires comparatively common electrical connection. The tooling for this exercise is relatively common and to engage robotic wire cutting a taught wire end effector was made using a standardized 80/20 modular framing system that enables a variable tool to be made at a low cost. Additionally a global registration system was developed that engaged each students stock to insure a consistent work object through out the process and register a static Y position relative to the programming workflow described below.

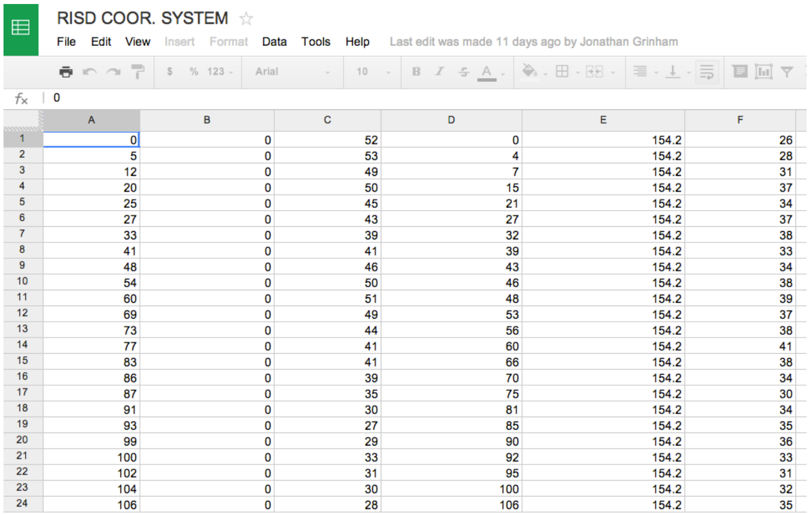
Processing-Based Workflow

In order to establish a ubiquitous geometric solver and data exchange platform, the Processing-programming environment was adopted for initial case studies. The bespoke Processing-to-robotic programming environment is the first of many tools being developed by these authors for module-based robotic programming. Module-based software for CNC manufacturing has become a popular alternative to cumbersome, CAD-CAM software, which require extensive training before use. Within this paradigm user-interfaces are developed for a single manufacturing process. This allows for higher interoperability for geometry generated from software outside of typical CAD suits (bitmaps, text, cameras). Furthermore, control of machine parameters are constrained to ensure proper machine interfacing, resulting in a more clear, one-to-one understanding of design parameters and machine capacity. The benefit of tool specific software can be observed in entities such as Autodesk’s 123D, a web-based software with individual design ‘apps’ ranging from 3D meshing, to 3D printing, to CNC laser cutting and the development of “Fab Modules” by MIT’s Center for Bits and Atoms for their international FabLabs (Gershenfeld 2005 and Keeter 2013).

Figure 6: A line in process. Here the student is measuring an elevation drawing informed by the isometric drawing in the foreground.

Figure 7: ABB- IRB120-based portable robotic teaching Cell developed by the Virginia Tech Center for Design Research.

A Processing-to-robotic module was chosen for many reasons, the primary being that Processing is free to download by all students who normally would not yet engage any 3D modeling environment. This widely used open-source platform has a relatively low learning curve and has been implemented in many foundation design studios through a number of two-dimensional drawing exercises. The Processing-to-robot programming environment developed for this study enables the input of measured hand drawn two-dimensional geometries through spreadsheet documents or comma-separated plain text files. In this case study, students were provided a GoogleDocs spreadsheet that could be downloaded and file mapped into the Processing code. The three-dimensional point array generates rail curves and mesh surfaces that can then be modeled and viewed in processing's 3D environment using OpenGL rendering and graphic computing. Surface modeling allows for an immediate feedback for students to ensure proper translation of point coordinates and design intent. While the processing workflow does provide a digital simulation, the lines used to create it are defined directly from the physical construct of the students. In this case there is a one-to-one correlation of what is seen in the simulation to what is drawn on the desk.



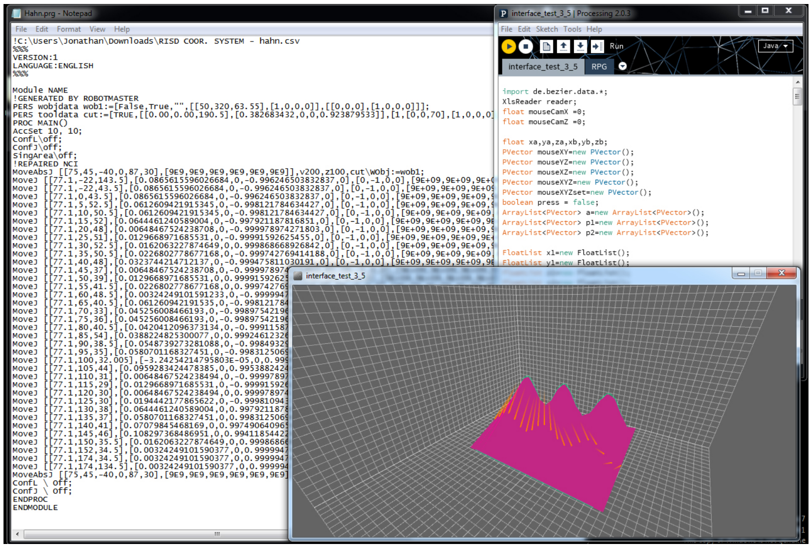
	A	B	C	D	E	F
1	0	0	52	0	154.2	26
2	5	0	53	4	154.2	28
3	12	0	49	7	154.2	31
4	20	0	50	15	154.2	37
5	25	0	45	21	154.2	34
6	27	0	43	27	154.2	37
7	33	0	39	32	154.2	38
8	41	0	41	39	154.2	33
9	48	0	46	43	154.2	34
10	54	0	50	46	154.2	38
11	60	0	51	48	154.2	39
12	69	0	49	53	154.2	37
13	73	0	44	56	154.2	38
14	77	0	41	60	154.2	41
15	83	0	41	66	154.2	38
16	86	0	39	70	154.2	34
17	87	0	35	75	154.2	30
18	91	0	30	81	154.2	34
19	93	0	27	85	154.2	35
20	99	0	29	90	154.2	36
21	100	0	33	92	154.2	33
22	102	0	31	95	154.2	31
23	104	0	30	100	154.2	32
24	106	0	28	106	154.2	35

8

Figure 8: Example spreadsheet interface used to cut the pieces shown in figure 1. Note the fixed Y coordinates 0 and 154.2 that correspond with the bounding edge of the clay block.

Using the Processing-to-robot programming environment a two-staged approach was used to convert the input, a comma separated document (CSV), to the needed Rapid Code used to operate the ABB IRB-120 robotic manipulator. First, the Processing-based programming environment provides a suite of geometric functions that facilitate the construction of tool paths based on predefined constraints. In this case, the two 'rail' geometries drawn by the students were created from data within the student spreadsheet and used to derive the points needed to visualize a ruled surface geometry and the center points needed to develop a tool path. In order to produce vector-based tool paths at a middle-domain an intermediate curve was constructed. Curve frames were then calculated based on a Z-dimensional offset and internal cross-product calculations derived from the angular rotation of the ruling line were used to construct directional vectors. The calculated resultant vector ensures the tool center point (TCP) remains in plane with, and normal to the ruling line meaning limited rotation about the wire vector or ruled lines. Vector geometry is then passed to an algorithm that calculates quaternion rotation at each point, or plane of movement. Once target location and rotation are derived from the CSV, user supplied data relating to work object origin, tool center point, movement type (moveJ or

10



```
!C:\Users\Jonathan\Downloads\RISD COOR. SYSTEM - hahn.csv
%%%
VERSION:1
LANGUAGE:ENGLISH
%%%

Module NAME
!GENERATED BY ROBOTMASTER
PERS wobjdata wob1:=[False,True,"",[[50,320,63.55],[1,0,0,0]],[[0,0,0],[1,0,0,0]]];
PERS tooldata cut:=[TRUE,[[0.00,0.00,190.5],[0.382683432,0,0,0.923879533]],[1,[0,0,70],[1,0,0,0]
PROC MAIN()
AccSet 10, 10;
ConfL\off;
ConfJ\off;
SingArea\off;
!REPAIRED NCI
MoveAbsJ [[75,45,-40,0,87,30],[9E9,9E9,9E9,9E9,9E9,9E9]],v200,z100,cut\WObj:=wob1;
MoveJ [[77.1,-22,143.5],[0.0865615596026684,0,-0.996246503832837,0],[0,-1,0,0],[9E+09,9E+09,9E+0
MoveJ [[77.1,-22,43.5],[0.0865615596026684,0,-0.996246503832837,0],[0,-1,0,0],[9E+09,9E+09,9E+09
MoveJ [[77.1,0,43.5],[0.0865615596026684,0,-0.996246503832837,0],[0,-1,0,0],[9E+09,9E+09,9E+09,9
MoveJ [[77.1,5,52.5],[0.0612609421915345,0,-0.998121784634427,0],[0,-1,0,0],[9E+09,9E+09,9E+09,9
MoveJ [[77.1,10,50.5],[0.0612609421915345,0,-0.998121784634427,0],[0,-1,0,0],[9E+09,9E+09,9E+09,
MoveJ [[77.1,15,52],[0.0644461240589004,0,-0.997921187816851,0],[0,-1,0,0],[9E+09,9E+09,9E+09,9E
MoveJ [[77.1,20,48],[0.00648467524238708,0,-0.999978974271803,0],[0,-1,0,0],[9E+09,9E+09,9E+09,9
MoveJ [[77.1,25,51],[0.0129668971685531,0,-0.99991592625455,0],[0,-1,0,0],[9E+09,9E+09,9E+09,9E+
MoveJ [[77.1,30,52.5],[0.0162063227874649,0,0.999868668926842,0],[0,-1,0,0],[9E+09,9E+09,9E+09,9
MoveJ [[77.1,35,50.5],[0.0226802778677168,0,-0.999742769414188,0],[0,-1,0,0],[9E+09,9E+09,9E+09,
MoveJ [[77.1,40,48],[0.0323744214712137,0,-0.999475811030191,0],[0,-1,0,0],[9E+09,9E+09,9E+09,9E
MoveJ [[77.1,45,37],[0.00648467524238708,0,-0.99997897
MoveJ [[77.1,50,39],[0.0129668971685531,0,0.999915926
MoveJ [[77.1,55,41.5],[0.0226802778677168,0,0.99974276
MoveJ [[77.1,60,48.5],[0.00324249101591233,0,-0.9999947
MoveJ [[77.1,65,40.5],[0.061260942191535,0,-0.99812178
MoveJ [[77.1,70,33],[0.045256008466193,0,-0.99897542196
MoveJ [[77.1,75,36],[0.045256008466193,0,-0.99897542196
MoveJ [[77.1,80,40.5],[0.0420412096373134,0,-0.99911587
MoveJ [[77.1,85,54],[0.0388224825300077,0,0.99924612326
MoveJ [[77.1,90,38.5],[0.0548739273281088,0,-0.99849329
MoveJ [[77.1,95,35],[0.0580701168327451,0,-0.998312506
MoveJ [[77.1,100,32.005],[-3.24254214795803E-05,0,0.999
MoveJ [[77.1,105,44],[0.0959283424478385,0,0.995388242
MoveJ [[77.1,110,31],[0.00648467524238494,0,-0.99997897
MoveJ [[77.1,115,29],[0.0129668971685531,0,-0.99991592
MoveJ [[77.1,120,30],[0.00648467524238494,0,0.99997897
MoveJ [[77.1,125,30],[0.0194442177865622,0,-0.99981094
MoveJ [[77.1,130,38],[0.0644461240589004,0,0.99792118
MoveJ [[77.1,135,37],[0.0580701168327451,0,0.998312506
MoveJ [[77.1,140,41],[0.07079845468169,0,0.99749064096
MoveJ [[77.1,145,46],[0.108297368486951,0,0.99411854422
MoveJ [[77.1,150,35.5],[0.0162063227874649,0,0.9998686
MoveJ [[77.1,152,34.5],[0.00324249101590377,0,0.999994
MoveJ [[77.1,174,34.5],[0.00324249101590377,0,0.999994
MoveJ [[77.1,174,134.5],[0.00324249101590377,0,0.999994
MoveAbsJ [[75,45,-40,0,87,30],[9E9,9E9,9E9,9E9,9E9,9E9]
ConfL \ off;
ConfJ \ off;
ENDPROC
ENDMODULE
```

```
import de.bezier.data.*;
XlsReader reader;
float mouseCamX =0;
float mouseCamZ =0;

float xa,ya,za,xb,yb,zb;
PVector mouseXY=new PVector();
PVector mouseYZ=new PVector();
PVector mouseXZ=new PVector();
PVector mouseXYZ=new PVector();
PVector mouseXYZset=new PVector();
boolean press = false;
ArrayList<PVector> a=new ArrayList<PVector>();
ArrayList<PVector> p1=new ArrayList<PVector>();
ArrayList<PVector> p2=new ArrayList<PVector>();

FloatList x1=new FloatList();
FloatList y1=new FloatList();
```

9

Figure 9: A screen capture showing the automated workflow derived from the spreadsheet in figure 8. Shown here are the Rapid code file, the processing interface and the resulting digital simulation including directional vector representation.

Figure 10: On the left five plaster-silica molds in the glass kiln post annealing and on the right a detail of a completed cast.

moveL), and velocity are pulled from the initial Processing interface and 'hard coded' through the use of a plain text file, which is also path mapped, read, and combined with vector data generated in the above description within the Processing environment to produce the final Rapid Code file, in this case a .PRG.

Kiln Casting

The glass kiln casting process utilizes an open-faced mold charged with Spectrum 96 Studio Nuggets. The molds were made with a plaster/silica mix using fiberglass needles and grog for strength as a "jacket layer". The molds were fired at 1600 degrees Fahrenheit and annealed for around 72 hours. This open-face mold technique is typically the first process taught during the technical Glass Casting and Mold-making course offered in the RISD Glass Department's curriculum. During the course, students are asked to design a "tile" or shallow relief using water clay. They then learn the process of turning this clay positive into a mold. First, the clay tablet is invested into plaster/silica. Once the investment material had set up, the clay is dug out and the negative of the form is left. Students then stack glass "nuggets" or tiny cubes of glass cullet into the mold. The mold is then loaded into the kiln and brought over slowly over.

12 hours to 950 degrees Fahrenheit to remove all the chemical water from the investment materials. The mold is then fired at 1600 degrees Fahrenheit until the glass cullet completely melts and fills the negative voids. More glass was charged at this point to adequately fill the molds. The glass was left at firing temperate for four hours to remove as many bubbles as possible. The kiln was then cooled as quickly as possible to 1050 degrees Fahrenheit to avoid devitrification of the glass. At this point the kiln is programmed to ramp down in temperature over 72 hours to room temperature using an annealing cycle for glass at 3-4" in thickness. Once cooled, glass was removed from the molds. Sharp edges were removed using a wet belt sander.

CONCLUSION

The industrial robotic manipulator offers the potential for design students to develop a material idea, the tool to realize it, and programmed spatial movements that allow rigorous iterations and exploration of key parameters and variables within a controlled material process. Despite the potential for incorporation at the foundation level the industrial robot is often relegated to advanced courses and research that tend to isolate the tool as an exception rather than a rule of integrated opportunity. In order for the field of Design Robotics to enjoy lasting impact it must become integrated within the fundamental design curricula. The design experiment described in this paper presents a singular example of the potential for the industrial robot to engage material, in a tangible manner, through an analogue design process that provides students with an acute awareness of the consequences of design decisions outside of the perceived 'black boxes' that are simulated digital design environments. Here the robot and the band saw are tools by which we realize design ideas within physical material/process parameters and therefore experiments such as these position the robot firmly in the context of foundation design education.

ACKNOWLEDGEMENTS

The prototypical exercise described here was supported by the Rhode Island School of Design Division of Foundation Studies, the Rhode Island School of Design Glass Department, and the Virginia Tech School of Architecture + Design, Center for Design Research.

11

Figure 11: A detail image of a completed glass block resulting from the analog design to robotic fabrication workflow.

REFERENCES

1. Andreani, S., Garcia del Castillo, J. L., Jyoti, A. Jyoti, King, N., and Bechthold, M.: Flowing matter: Robotic fabrication of complex ceramic systems. in: Proceedings ISARC 2012, Eindhoven, The Netherlands.

2. Bechthold M. and N. King. 2012. "Design Robotics: A Strategic Research Approach" , Proceedings of the 2012 Robot In Architecture, Art, and Design Conference; Springer, Vienna, Austria.

3. Gershenfeld, N.A. 2005, Fab : the coming revolution on your desktop--from personal computers to personal fabrication, 1st edn, Basic Books, New York.

4. Keeter, M. 2013, Hierarchical Volumetric Object Representations for Digital Fabrication Workflows, Master of Science in Media Arts and Sciences edn, Massachusetts Institute of Technology, Cambridge, MA.

5. Pool, S. 2003. 'Pumping Up: Digital Steroids and the Design Studio' Published in ACSA National Conference Proceedings, pp. 402-405.