Robotic Material Renaissance: Industrial Robotic Arms for Architects

Perkins+Will Building Technology Lab and Autodesk BUILD Space, Boston

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Abstract. Industrial robotic arms, when used by designers, have the potential to restore a humane sensibility to the construction process. Their flexible 6-axis movement, highly customized heads, and ability to connect to the digital world through direct simulations and streamlining are turning designers into high-precision fabricators of custom objects and assemblies. This paper looks at the potentials of industrial robotic arms in architecture when combined with material programming of phase-changing materials. The project executed by the authors did not require a technical background in robotics, programming or material science and illustrates a streamlined digital strategy for designers working with robots. This paper presents a novel and materially generated fabrication process that 3D prints and stretches bioplastic Polycaprolactone while controlling its extruding and freezing temperatures, pulling speeds and angles using highly customized heads mounted on robots. This approach challenges current 3D printing techniques and brings back the material intelligence to automated fabrication processes resulting in unique structures with physical material behavior that informs the digital fabrication processes. The result is a design approach to industrial robotic arms in architecture where robots act as a mediator between the digital world and the physical material based on simple BIM logics and customized endeffectors. Founded on previous work held at the Architectural Association School of Architecture Design Research Laboratory, this paper extends the work under Perkins+Will Building Technology Lab in collaboration with Autodesk BUILD Space as an applied research initiative to build a thermoplastic panel for prefabricated classrooms.

Keywords: Stretching Plastic, Robots in Architecture, 3D printing.

1 Introduction

1.1 Background & Motivation

Design and construction processes adapt and change to meet human needs and the environment we live in. The past decade has brought small-scale fabrication opportunities to designers through collaborative robots and low-cost 3D printers. This paper looks at cutting-edge technology, industrial robotic arms, as the new revolution in architecture for their unique ability to connect the digital world and physical material world together. As stated by the pioneers of industrial robotic arms in architecture by Gramazio & Kohler architects & researchers, “The Robot…connects the world of immaterial logic with that of material construction in the most direct way” (Argyros, 2016)

To introduce robots into architectural practice, it helps to think of a robot as a human arm that can accept a variety of hands, called ‘end effectors’ which can perform various functions. This conceptual approach allows the architect to be in control, not just of the formal physical design, but as well as the process of fabrication and the construction technique itself and in some cases the tools used to build with. As Gramazio & Kohler architects sate, “By defining the robot’s hand –also called the “end-effector” – and determining its movements, we teach the robot a desired type of construction” (Gramazio & Kohler, 2008)

In this context, the role of architects as virtual designers who leave fabrication and construction to others is quickly being replaced by a role that includes material programming, design of the fabrication process and a design approach that couples an empirical understanding of material constraints with appropriate fabrication techniques. This new role is made possible by efficient software workflows that convert virtual intent to physical action utilizing industrial robotic arms precision and customization along with programming architectural materials to produce a bottom-up approach to robotics and materially driven design and fabrication processes.

In this paper, we present an approach to digital fabrication by which industrial robotic arms play a key role in connecting computer-generated designs to constructing the designs through materially driven digital fabrication techniques. The research discusses an approach to industrial robotic arms and computational tools that synthesize them as design tools without requiring prior knowledge of any specific robot coding language or software code.

In addition, the research interrogates the bridging role that designers must play between the digital design and the physical end product. The role requires: interrogation of the formal opportunities presented by construction material properties within automated robotic processes, streamlining workflows for software (design and scripts) and hardware (automated robotic movement), and the development of physical end effectors that integrate with robotic automation.

1.2 Literature Review

Master craftsmanship in building construction declined with the advent of the industrial era. Designers and architects who appropriate fabrication technologies to augment the design process are uncovering the opportunities for architects to be craftspeople of the designs they envision. Similar to the ability of a painter, illustrator or sculptor to physically produce the mental object in their minds, architects can now appropriate robotic technologies to engage in physical architectural creation by developing the robotic methods of converting designs into built form. As described by Gramazio & Kohler, “In the digital age, our concept of serial repletion, which was the product of industrialization, is being transformed much in the same way as the opposing romantic conception of the “natural” uniqueness of craftsmanship. A language of diversity is emerging that gains its identity through the design of processes rather than the final forms” (Gramazio & Kohler, 2008)

Thus, the revolution here is a *Machinery Renaissance* where *Digital* and *Machinery* tools such as robots must be used in a “craftsmen” design manner, rather than just a mass production tool. This development liberates the AEC industry from repetition as the means to economy. Traditional digital fabrication methods tend to generate the form digitally first without a direct connection of the fabrication method, whether it is an additive process, such as 3D printing, or a subtracting one, such as a CNC router machine. A new approach to digital fabrication is a materially driven approach based on the material properties. Therefore, the method of fabrication is part of the design process rather than a distinct and subsequent action on a block of material regardless of the material potential at hand (Foley & Johns, 2014).

A relevant example of a project that uses a phase changing plastic in a depositing manner by an industrial robotic arm is the ‘Sense It’ workshop held at Rob Arch conference and workshop. The ‘Sense It’ group combined robotic plastic deposition (RBD) with temperature and distance sensing as a first case of materially directed generative fabrication. The customized endeffector melted the polypropylene granules into a viscous mass that was extruded through an aluminum nozzle. The shape and size of the nozzle affected the extrusion of the plastic deposition. By pausing the extrusion process in the code and moving the nozzle upwards after each deposition, it prevented the plastic from hardening on the nozzle itself. Due to the material intrinsic properties, the pouring mass hardened within seconds, right after its deposition, resulting in a lattice structure (Abrons, et al., 2014)

Recently, plastic in architecture and construction is experiencing a renaissance where architects are exploiting the material’s diverse properties in search for new forms of construction methods appropriate to plastics. Andreas Harris research serves as a good example of material programming through understanding the intrinsic intelligence and behavior of bio-resins. The aim of Harris’s project is to develop a structure based on self-forming and self-optimizing morphologies. These morphologies are derived from the manipulation of viscous materials using both physical experimentation and parametric computation to simulate in a digital environment the physical processes, such as fluids and other malleable materials that have the ability to harden under certain pressures. The material explored by Harris is a bio-resin, which is manipulated using plates, and pulling techniques to create the material structures as shown in Figure 1 (Harris, n.d.).

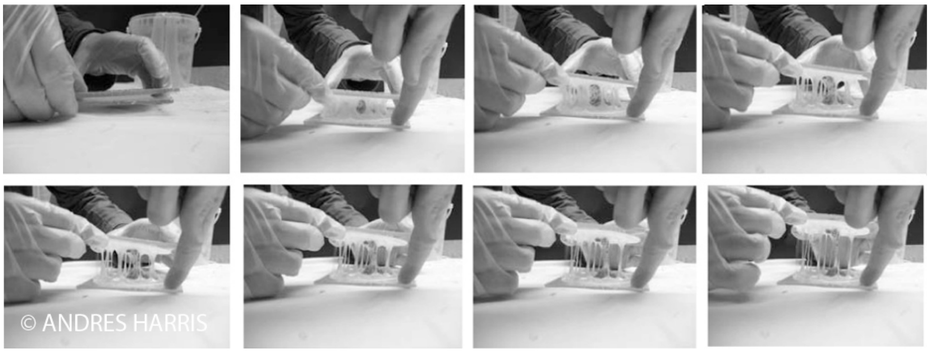

Fig. 1. Using plates and pulling as a technique to create material structure, “2.0 Form-Finding”, ©Andres Harris, Architect at Foster & Partners; London.

Along a similar line of inquiry, research by Skyler Tibbits et al, MIT (2014) develops a methodology for “4D printing” by exploiting the varying hydroscopic properties of two (or more) different plastics deposited in a 3D assembly. Using multi-material 3D printing to fabricate parts consisting of a “rigid plastic base and a material that expands upon exposure to water” (Raviv, et al., 2014) complex geometrical transformations or structures – in particular, those not possible from the initial fabrications – may be achieved. This work is further developed by the same research group with respect to more nuanced temporal characteristics as well as for 3D-printed wood (Correa, 2015)

2 Project Context

As a research leading design firm, Perkins+Will Building Technology Lab is researching prefabrication as a means of delivering projects faster, cheaper and with higher quality. Perkins+Will Technology Lab is focusing on the design implications of the prefabrication process and the potential for fabrication automation to give designers more design liberty as well as control over the physical product of the fabrication process. Design using robots is being developed through empirical testing and experimentation with various (endeffectors) and materials. Embedded in this work is the understanding that architects of today and the future are designing not only the buildings to be built, but the digital and physical tools used in that process. As a framework for investigation, we are designing and fabricating wall panels for Perkins+Will firm-designed re-locatable classroom building called Sprout Space. The fabrication is taking place at Autodesk BUILD Space, Boston, using automated equipment including multi-axis milling machines and industrial robotic arms of various sizes. This research project explores the use of multiple robotic arms working collaboratively to create wall panels by means of thermoplastic material. The research targets challenges that lie between digital design and fabrication.

3 Methods

The essence of the designer-friendly approach to fabrication with robots is to use any BIM software familiar to designers to generate z-axis planes along the geometry paths that the robot tool path will need to follow. We conducted the robot's path in various 3D BIM familiar architecture software that are used in the industry to create buildings to prove that any architect with the basic digital knowledge of architecture 3D software can design with industrial robotic arms.

The fabrication method established in this research, which controls the robotic movement by familiar 3D modeling techniques, is dependent on the material manipulation process, and construction technique. The fabrication process involved design of tools, or 'end effectors' mounted on robots. A strooder machine, filament maker and three endeffectors in total were used: two 3D printed pulling endeffectors and one extrusion gun to extrude (3D print) the material as shown in Figure 2. The material manipulation process involved 3D printing deposition and stretching of thermosetting plastics. Instead of traditional addition or subtractive construction techniques, we allow the intrinsic potential of the material – its capacity to stretch when heated – to inform the fabrication approach. Stretching the material as a means of controlling and establishing the physical form has a direct effect on the formal approach to the thermoplastic wall panel design.

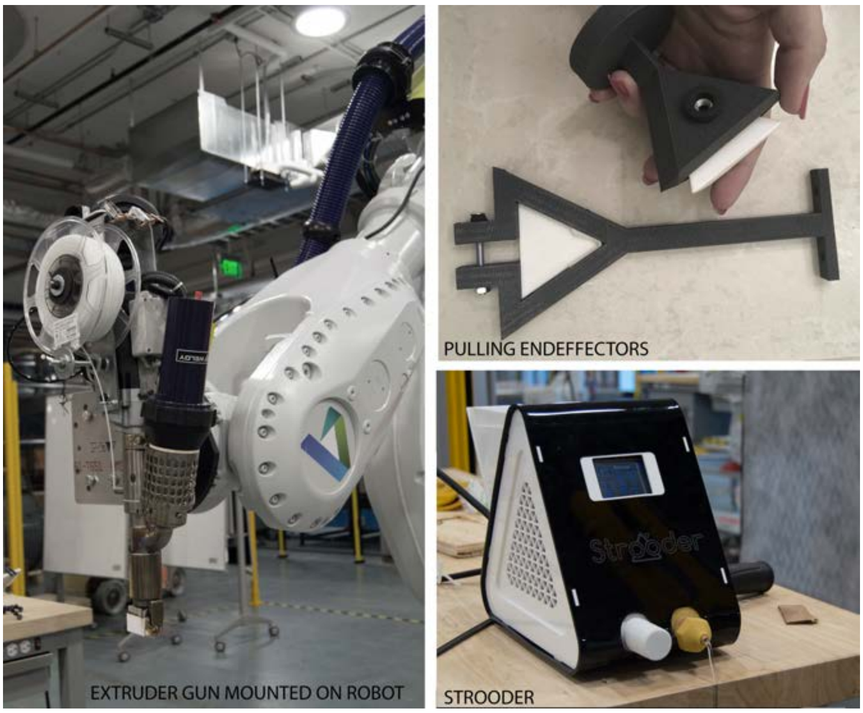

Fig. 1. Demonstrating the tools used to fabricate the panel, Perkins+Will Building Technology Lab at Autodesk BUILD Space, Boston, 2016.

The panel geometry design, as illustrated in Figure 3, is defined by the formal opportunities found within stretching heated plastic before cooling and hardening. Prefabricated PLA nodes are 3D printed and represent the joints of the panel. The beams are 3D printed in high temperatures on the faces of the PLA nodes and stretched, while still hot, through customized endeffectors attached to the robot. The beams centerlines directly represent the robot tool paths by which the positive z-axis of the tool path aligns with those of the beams. The intersection of the beams is the 3D printed PLA tetrahedron nodes in reality.

Therefore, in our approach there is a direct relationship between the digital representation of the panel and physical outcome and the robot tool path. This approach simplifies the tool path geometry needed for the industrial robotic arm to move in space.

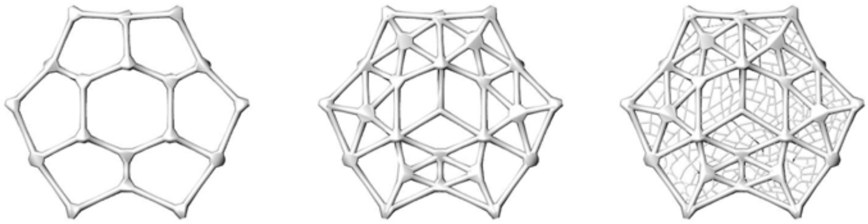

Fig. 2. Thermoplastic Panel Design, Perkins+Will Technoloy Lab, 2016.

3.1 Material Programming

After few experiments in extruding different plastics, we chose bioplastic Polycaprolactone to best demonstrate this approach due to the great design opportunities it has in its ability to be formed, reused, melted and stretched. Polycaprolactone is used mainly in medicine as a 3D printed implant and cast. It served as a good material to study for its fairly low melting point at 60ºC, high abrasion resistance and quick setting point at moderate temperatures (Perstorp, 2018). Polycaprolactone initial physical state is solid granules that transform into a putty-like viscous mass when heated by which it can easily bind to itself or the material behavior of Polycaprolactone informed the digital design of the geometry and fabrication processes, where the robot and the material constraints are all dependent on each other. The geometry design, which is a thermoplastic panel, utilized the stretching ability, yet fast setting time and strength, of Polycaprolactone to its best by allowing the robot's fabrication paths to follow the actual design of the panel. Our experiment takes steps to address and deploy (1) the functional, structural and aesthetic goals for the fabricated structure, (2) the capabilities of available and customized tools being used to control the fabrication process, and (3) the behavior of the material under such constraints. Designing this fabrication process did not require scientific knowledge of why, for example, the molecular structure of PCL results in a melting point of 60ºC and distinct elastic, 'taffy-like' properties when melted; nor did it require mechanical design of the inner-workings of the extruder gun being used as a deposition device. Instead, ready-made and designed 3D printed tools combined with empirical used polymer, currently, in the manufacture of polyurethanes and was one of the first raw materials to be extruded through a RepRap extruder.

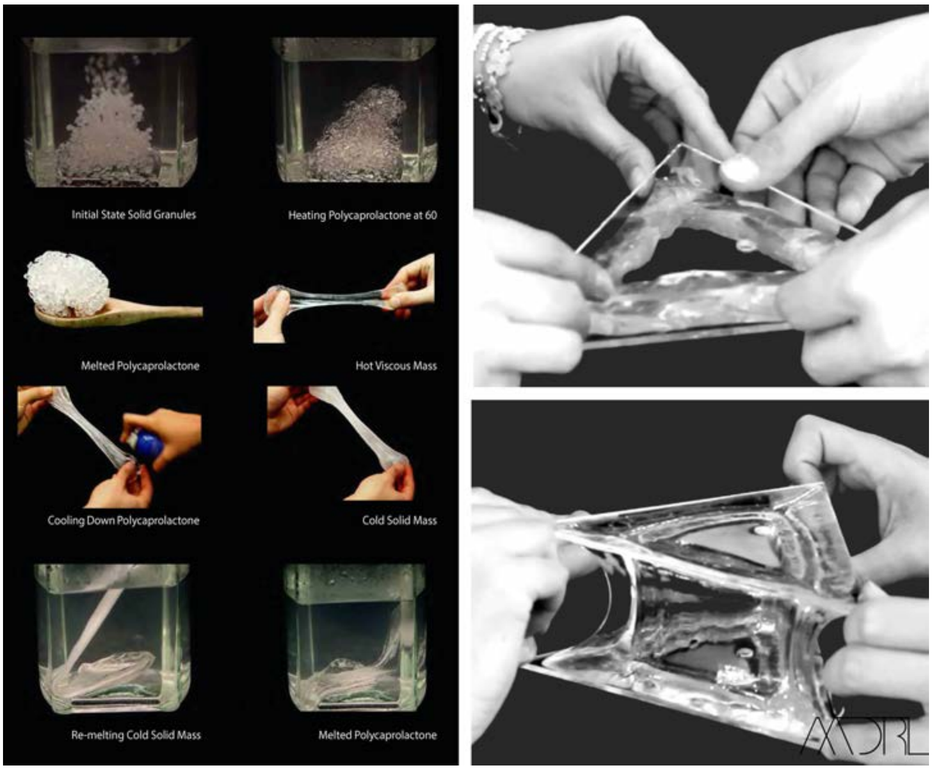

Fig. 3. Demonstrating the phase changing cycle of Polycaprolactone, Master's Thesis Dissertation, Soulaf Aburas, Maria Paula Velasquez, Giannis Nikas, Mattia Santi, Shajay Bhooshan Studio, AADRL; London, 2013-2015.

The material behavior of Polycaprolactone informed the digital design of the geometry and fabrication processes, where the robot and the material constraints are all dependent on each other. The geometry design, which is a thermoplastic panel, utilized the stretching ability, yet fast setting time and strength, of Polycaprolactone to its best by allowing the robot's fabrication paths to follow the actual design of the panel. Our experiment takes steps to address and deploy (1) the functional, structural and aesthetic goals for the fabricated structure, (2) the capabilities of available and customized tools being used to control the fabrication process, and (3) the behavior of the material under such constraints.

3.2 Filament Extrusion

Initial material tests began with using Polylactic acid (PLA) filament; this was a choice motivated by concerns for environmentally friendly features regarding the material's renewable resource content, minimal toxicity hazard, and recyclability. The PLA filament, of a diameter 3mm, was ready made and purchased. Material deposition tests with our industrial extruder gun were conducted. Results show the PLA filament tended to cool down too quickly to allow adequate time for manipulation, proved to be prone to burning before ever achieving suitable malleability and was brittle in its nature as shown in Figure 5. The second material we tested and proved to work the best was Polycaprolactone (PCL), which came in the form of pellets, which allowed us to create our filament.

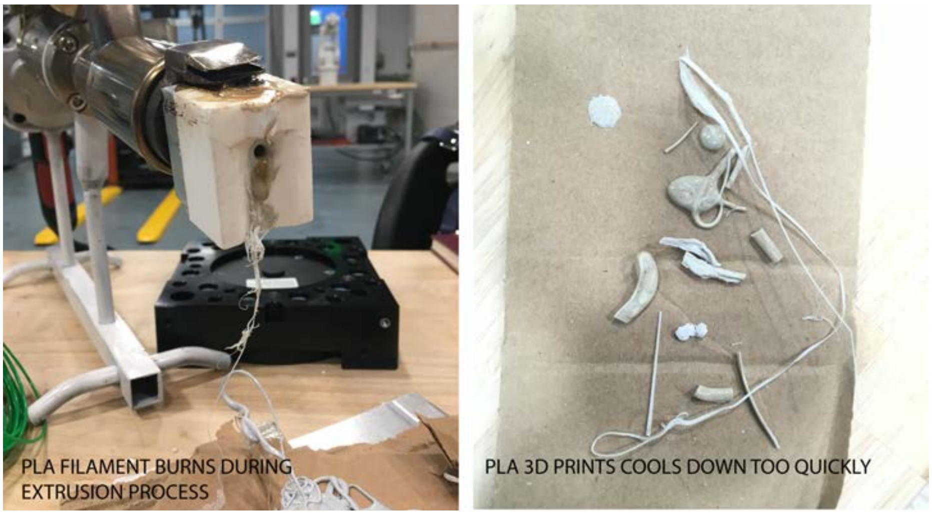

Fig. 4. PLA filament heating and 3D printing tests show that heating range was too high for the material and cooling process was too quick for stretching and the material is brittle in its nature, Perkins+Will Building Technology Lab at Autodesk BUILD Space, Boston, 2016.

Polycaprolactone (PCL) was the medium of research and material programming of previous work done by one of the authors with "Osteobotics" group at the Architectural Association School of Architecture Design Research Laboratory under Shajay Bhooshan Studio. PCL has proven to be feasible for this job as well since the filament produced with PCL was easy to control when produced and did not burn or sag while stretching. Multiple experiments were conducted via the filament maker and extrusion gun to find the right temperature and speed for PCL filament making and extruding as shown in Figure 6.

Fig. 5. PCL filament making, 3D printing and stretching experiments, Perkins+Will Building Technology Lab, Autodesk BUILD Space, Boston, 2016.

We used a Strooder filament maker; to extrude PCL pellets into 3.0 mm ⌀ (nominal) filament, under varying warm-up and steady-state temperatures. For all PCL filament test trials, the output point of the filament maker nozzle was elevated approximately 1000 mm above a flat surface, which in this case was a concrete floor of the workspace. The nozzle was also positioned such that the first few 200 mm of semi-molten filament was allowed to 'roll' off the corner of the nozzle at an approximately 45º angle and fall in coils on the floor for later collection.

Six PCL trials (enumerated I-VI) were performed for varying warm-up and steady-state temperature conditions, and the qualitative characteristics of the resulting filament sample were noted as shown in Table 1. The settings in Trial "VI" were adopted for the rest of the experimentation.

Table1: Summary of PCL filament extrusion test conditions and results.

ID	Warm-Up (ºC)	Steady-State (ºC)	Result Description
I	60	60	Pellets jammed at nozzle.
II	75	60	Few inches of filament produced, followed by jamming.
II	140	100	Filament diameter too small; moderately severe excess

I			stretching.
IV	100	90	Moderate excess stretching.
V	100	75	Slight stretching.
VI	100	72	Minimal stretching; suitable filament produced.

3.3 Extrusion Gun

Second, given the capabilities of an available off-the-shelf extrusion guns for receiving, heating, and depositing plastic materials, we used a commercial filament maker to custom-extrude PCL filament to the required diameter. This, in turn, required control over the feed rate, temperature, and other flow-related characteristics of the filament extrusion process. The specification of the plastic material, plastic extrusion gun and the custom filament extrusion process allows for more direct control over the fabrication process, which in turn, modulated the aesthetic and performative results of the extruded beams. The made PCL filaments were fed into the extruder, supported on a spool, and the temperature and speed of extrusion were controlled. The extruder machine was mounted on a 6400 ABB industrial robotic arm and its switching on and off button was digitally controlled via digital inputs transmitted through the robotic arm to help automate and facilitate fabrication process smoothly. The job of the extrusion gun was to 3D print a hot viscous mass of PCL in a controlled quantity, speed, and temperature.

3.4 Robotic Workflow

To best explain industrial robotic arms in context of architecture, we simplified their movement to a series of positive z-axis planes in which the robot's tool tip has to follow. Thus, theoretically speaking, we have to imagine that there is a floating plane at the tool tip of the robot, and one need to align the plane to similar planes along a path in order to move a robotic arm. These planes were defined digitally in common architecture software through digital surfaces or through scripting creating three points in space that defined the origin, x axis direction, and orientation or normal (z-axis) of these planes. Regardless of the rotation of the planes in the x and y directions, the orientation was always pointing outwards away from the robot in the positive z-axis of the robot's tool tip plane.

A robotic workflow was designed and created to fabricate the thermoplastic panel, in which the flow was built around the material & industrial robotic arms constraints and behavior. The material main constraints were the stretching limit range between 70-150 mm based on the 5mm sided equilateral triangular face of the tetrahedron node and the material shear-angle tolerances as shown in Figure 7, which was obtained from previous studies. The robotic constraints lie in the use of the right size of the robot to the needed tasks versus the reach of the robot. The reach of any robotic arm to any point in space is determined mainly by its size and in some cases its previous position in space. For example, just like the human arm, the robotic arm may need to unwind before reaching out to the next target. Moreover, the larger the robot, the wider its reach, yet the heavier it gets and subsequently the larger the load it can carries.

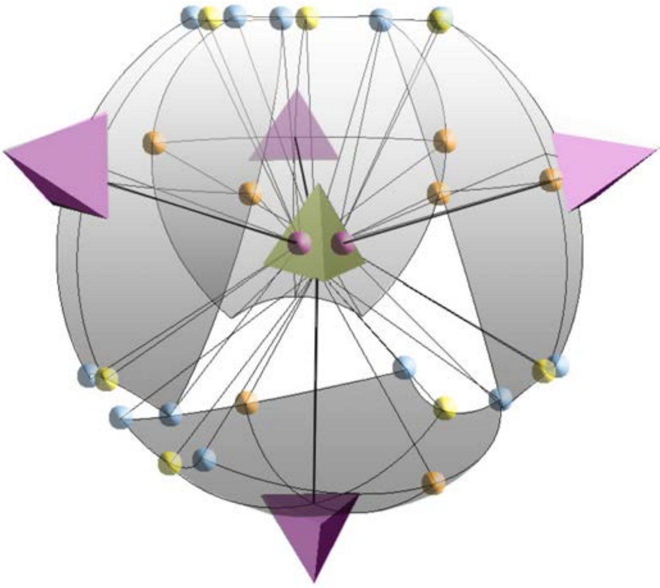

Fig. 6. PCL angle shear tolerances summary obtained from physical material experiments and digital simulations, Master's Thesis Dissertation, Soulaf Aburas, Maria Paula Velasquez, Giannis Nikas, Mattia Santi, Shajay Bhooshan Studio, AADRL; London, 2013-2015.

Appropriate industrial robotic arms were chosen based on the size of the panel and the endeffectors weights. The 120 ABB robot was found suitable for carrying the tetrahedron nodes and pulling the lattice structures due to its small size that enables the robot to maneuver through the pulled structures and yet large enough to stretch in all the designed directions of the panel. The larger 6400 ABB robot was chosen to handle the heavy extruder machine due to its high payload capacity and its path did not require a lot of maneuvering except to 3D print the hot plastic on the face of the node. The robots were arranged wherein both robots can work in harmony and do not clash with each other, creating a multi move robotic fabrication system. The larger 6400 ABB robot was fixed to the ground, so we mounted the smaller 120 ABB robot on a height adjustable table and moved it to a position in space where the two can meet and work together effortlessly in the shared working area as shown in Figure 8.

The fabrication process consisted of two tool paths: the 3D printing tool path and the stretching tool path. The 3D printing tool path is a simple path where the two robots meet in space with the small 120 ABB robot positioning the node face-up towards the tip of the extrusion gun, which is mounted on the large 6400 ABB robot. After the plastic is extruded on the node's face, the smaller robot moves to start the main part of panel fabrication, which realizes the panel through stretching.

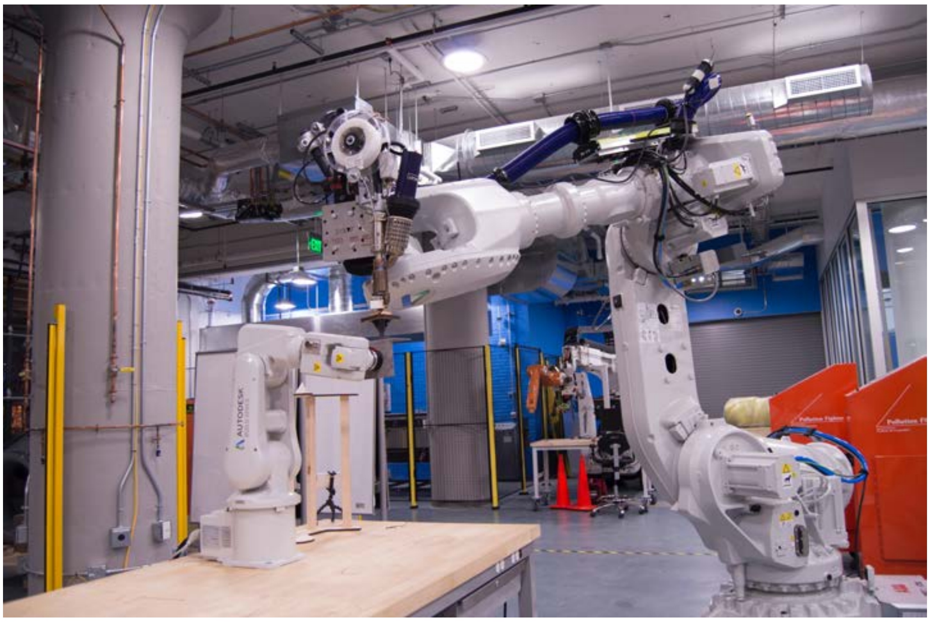

Fig. 7. Industrial robotic arms arrangement, Perkins+Will Technology Lab at Autodesk BUILD Space, Boston, 2016.

The stretching fabrication process of the panel was simplified to repeatable robotic workflows called tool paths, where the same tool path was used to generate different beams by just rotating the fabricated panel. This simplification, as shown in Figure 9, resulted in using only two tool paths to fabricate the whole panel. Both tool paths were built upon basic geometric relationships between planes so that they can be generated in any basic architecture 3D software. In all three architecture-software, the digital model consisted of a first plane parallel to a fixed tetrahedron node, a second plane, which represents the final position of the pulled node and the stretching planes in between. The first node is either a node mounted on the working table or a previously stretched node. Regardless, a tetrahedron node was digitally modeled. All tetrahedron nodes are of 50 mm side equilateral triangles. The first plane is always parallel to the fixed tetrahedron node and offset by 5mm in the negative z-axis to accommodate for the hot plastic thickness. Then a second plane matches the second node's final position and face orientation. This time the orientation of the second plane matches exactly where the second node needs to be positioned and no offset is required. The positive z-axis orientation of the second plane points away from the node's final position so that the tool tip ends the pulling with the face of the second node facing straight into the pulled beam.

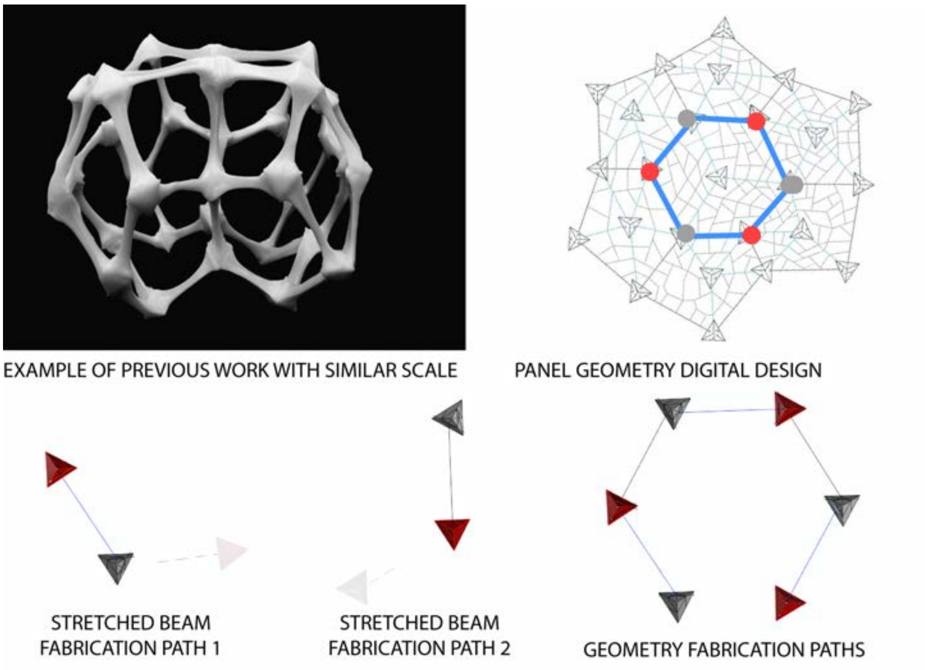

Fig. 8. Relationship between thermoplastic panel design geometry and the fabrication paths geometry, Perkins+Will Building Technology Lab, 2016.

Finally, a line is constructed between the center point (origin) of the first plane and the center point (origin) of the second plane with interpolating planes along the line. The z-axis orientation and direction of the x, y-axes of those interpolating planes are adjusted to match those of the first and second planes. This path represents the "pulling" path and direction.

4 Results & Reflections

The stretching factor in this approach is different from the freeform 3D printing with robotic arms in which the formal outcome of the material is unique than that modeled in the software. This uniqueness is due to the material behavior in real time while construction, which gives the stretched, beams their triangular section through pulling and surface tension and not through 3D printing the form in layers. Based on the surface tension behavior of the material and its structural integrity we proposed and designed a robotic workflow that exploits the material intelligence as a design driver and the robot as a fabrication tool through the digital interface of common architecture software. This allowed us to focus on the design of the fabrication process as a whole and the integration of its components rather than on technical issues such as robot's code or unnecessary digital technical concerns.

The tool path geometry was repeated and constructed in Autodesk Dynamo software and Rhinoceros software and grasshopper 9.1 plugin for Rhinoceros 5, which are all familiar 3D software to architects. All three-tool path geometries could be translated into the same robot's code language. Prior knowledge to coding was not needed nor robotics language. All was needed was to understand the relationship between the panel design, the robot path and the material behavior which enabled the link between the two. Therefore, this approach presents industrial robotic arms as the link between the digital workflow design and the material, and the material as the enabling medium to translate the digital panel geometry design into reality. Therefore, the robot pulling paths of the material were derived directly from the 3D architecture software; the only things that were controlled via robotic software or code were the speeds and digital inputs or delays. The fabrication process was held using two ABB robots at Autodesk BUILD Space at Boston using an extruder machine and PCL custom made filament as shown in Figure 10 below.

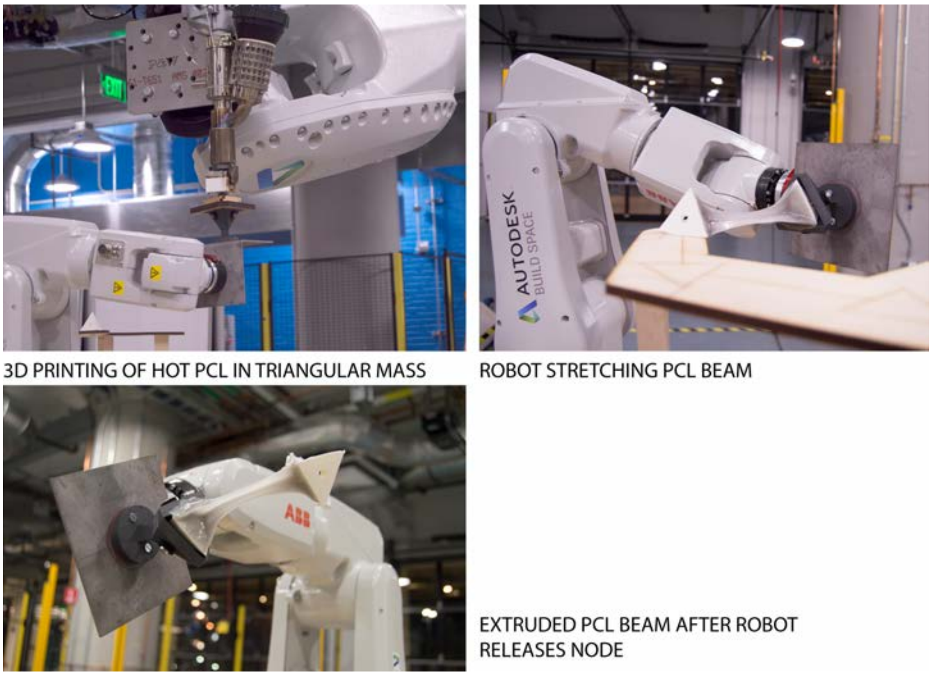

Fig. 9. Fabrication process of thermoplastic panel, Perkins+Will Building Technology Lab at Autodesk BUILD Space, 2016.

For extra safety measures, we used a robotic simulation software for robots, and we simulated the whole fabrication process virtually before running the actual fabrication. The simulation software requires the digital modeling of the tool 'endeffector' and identifying the robot, which is connected through its IP address to the software and runs the simulation through a text code file.

Conclusion

The designer-friendly approach this paper presents addresses fabrication with industrial robotic arms in architecture using any BIM software familiar to designers to program the material fabrication and behavior processes. Therefore, the method established in this research controls the robotic movement by familiar 3D modeling techniques and is dependent on material manipulation processes. Instead of traditional addition or subtractive construction techniques, we allow the intrinsic potential of the material – its capacity to stretch when heated – to inform the fabrication approach. Stretching the material as a means of controlling and establishing the physical form has a direct effect on the formal approach to the thermoplastic wall panel design.

The role of architects as virtual designers who leave fabrication and construction to others is quickly being replaced by a role that includes material programming, design of the fabrication process and a design approach that couples an empirical understanding of material constraints with appropriate fabrication techniques. This new role is made possible by malleable architectural materials, efficient software workflows that convert virtual intent to physical action, and robots that can execute custom tasks with high precision.

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