Isoprototyping

Rapid Robotic Aided Fabrication for Double Curvature Surfaces

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IsoPrototyping is a research initiative, undertaken at the Institute fur experimentelle architektur.hochbau, within the context of the Vertiefung Hochbau and Sonderkapitel des Hochbaus courses, which specialize on building construction. Through the case study of an iso-surface spatial configuration, this research targets the exploration of innovative digital prototyping methodologies, that would allow rapid and cost-efficient fabrication, capable of manufacturing any given double curved surface. The ABB industrial robots of REX-Lab programmed in combination with custom designed, recalibrated dry-mold, surface-producing apparatus, formed the framework for a proficient, yet flexible, process describing and fabricating implicit non-linear systems.

Keywords: *industrial robots, pin-board, rapid-prototyping, dry-recalibrated mould, digital-fabrication*

INTRODUCTION

The Vertiefung Hochbau and Sonderkapitel des Hochbaus course's incentive derives from the observation that despite the increasing popularity of these implicit morphologies within the architect's agenda, the fabrication outcome has been mostly confined to 3d-printing. While the provided product is acceptable in terms of representation, is not however contributing to any advancement towards larger scale fabrication. In large scale projects that include paneling or cladding with constant, yet relatively smooth, change of curvature without any standardization or breakdown into repeatable components, the material waste for one-time-usage moulds can exceed by far in volume, the actual product.

The research question raised, therefore, was whether a non-conventional fabrication method could be developed having significant advantages over other known rapid customization procedures, yet maintaining an adequate level of accuracy. The hypothesis was formed around the argument of whether via a flexible and re-usable tool, capable of being re-calibrated rapidly and accurately via robotic control, a transformable dry mold could be developed to the point where the whole fabrication system could be superior in terms of cost-efficiency, material waste and production pace.

A generalization of this process is intended up to the level of any given double curved surface, for a large scale façade project, while addressing parameters such as choice of material, the healing process, the complexity of the model and the post-fabrication assemblage. In this context, the selection of an iso-surface structure (figure 1) proved a demanding task, due to its constantly changing curvature over a vast range of scales and sizes within a single model.

Figure 1
The initial Iso-surface case study

BACKGROUND RESEARCH

Similar approaches exploring double curved surface fabrication methodologies provided a hands-on experience on the challenging character of this investigation. Notable are the 3d puzzle prototypes by Axel Kilian (Kilian 2003) and the flat aluminum stripes articulation of self-supported implicit surfaces from Marc Fornes (Fornes 2011) , forming structures resembling minimal and iso-surface configurations. While these two focused on a more linearly tessellated assembly, Iso-Prototyping instead of creating a repetitive or flexible component that by assemblage generates multiple varieties of double-curved surfaces, looked into creating a flexible re-usable mechanic system that generates infinite number of non-identical components.

On the robotic fabrication side, a similar and synchronous approach of heat forming plastic plates was developed by RobotsInArchitecture (Braumann and Brell-Cokcan 2013) , where the heating and forming process were confined on a local topological level, rather than on the overall module.

ISO-SURFACES

Reasons for choosing iso-surfaces as a case study

The iso-surfaces case study was selected due to their intrinsic nature deriving from the two-dimensional isolines (Greek ίσος=equal). Iso-surfaces in a similar fashion represent 3D-topology of the same value within a certain spatial volume, being primarily represented by the marching cubes algorithm (Lorensen and Klein 1987) , which extracts the polygonal mesh of a three-dimensional scalar field or voxel-space. Their emerging implementation in contemporary architectural research, origins from their inherent capacity to generate a formal language of an otherwise un-achievable spatial intricacy.

Digital experimentation with iso-surfaces commenced via the Grasshopper3d platform , utilizing a series of add-ons to render designable their reciprocal properties. In particular Nudibranch [3] to generate the value-fields, Millipede [2] for polygonizing the scalar field (Bourke 2012) and Weaverbird [4] for smoothing the resulting mesh. The design output depended greatly on user-defined constraints, with only global design restriction being that, the iso-surfaces had to be in pairs with a constant distance between them. Hence a substantial amount of complexity emerged, with necessity of being realized into physical models via several methods of fabrication.

Different fabrication techniques

A series of different fabrication techniques where explored, prior to the final decision to push forward the recalibrated iso-machine, in order to assess different material behaviours, the surface quality of the result and the required time, cost and material waste generated per piece. These were:

- Waffled structures (cross linked profiles made out of laser-cut mdf) to which a thin metal mesh was attached on both sides as a base for plaster being applied at the end (figure 2).

- CNC milled foam moulds for casting plaster (figure 2).

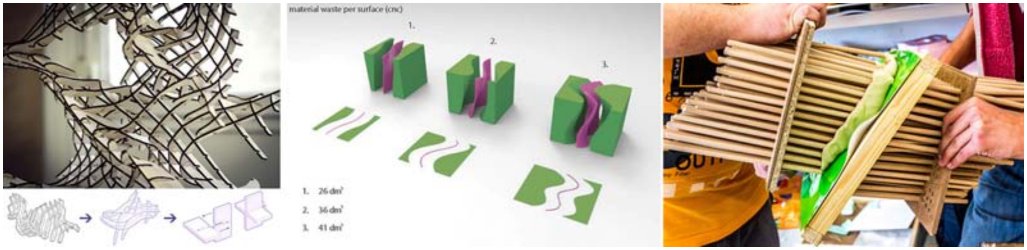


Figure 2
Testing different fabrication techniques

- Pressure application on heated polystyrene plates (figure 2).

THE ISOMACHINE

A Transformable dry Mould

As a solution on how to achieve a continuous, smooth and double-curved surface, a choice was made to work upon the concept of the decorative toy 'Pin Art' (figure 3), where an array of metal pins is being distributed between three boards that when pressure is applied from one side, the pins move creating a pixelated representation the object that is pushing them. The same logic was implemented in the examined machine prototypes, with the difference being that no shape applies pressure on the pins. Rather they get positioned by robots controlled by an algorithm. As a result the outcome of this positioning is then used as the mould for forming the final surface.

The 'Pin Art' concept provides an infinite number of possible surface describing configurations, capable of operating as dry moulds manipulating heated polystyrene boards bought right off the local market, overcoming the dependence on liquid-form materials with time-consuming setting requirements.

Similar Approaches

In terms of similar approaches to a recalibrated mold, the "Digital Clay" project (Zhu and Book 2006) created a haptic surface described as a *"3D Monitor whose pixels can move perpendicularly to the screen to form a morphing surface"*. Although aimed for an entirely different and bi-directional interactive purpose, the resulted 2,5D computer-controlled tangible surface is similar to our proposal. Yet with the introduction of fluid power for actuation, sensors and micro-controllers aiming into constructing a *"massive hydraulic actuator"*, the decision to have all the components integrated into the "Digital Clay" can not only increase the cost but also increase malfunctions when such a delicate mechanic system is employed to apply deforming-pressure to hot polystyrene surfaces.

Similarly the FEELEX (Iwata et al. 2001) developed a haptic surface by employing DC motors with a minimum of 6x6cm array grid and resolution. This limitation due to the size of the smallest motor available (4cm diameter) resulted into the FEELEX-2 which incorporated a piston-crank mechanism to allow one servo motor to calibrate more than one rod,

Figure 3
The Pin-Board Game

in this case 25 - a grid of 5x5. Yet this had as a limitation the small height displacement of the rods, linked to the rotation of the servo motor and the linkage.

The presented in this paper approach towards all the above projects was to overcome the limitations arising from incorporating moving mechanisms (either DC motors or fluid actuators) into the machine such as low rod resolution, vibrations, small height movement, multiple servo motors or delicate equipment non-resistant to pressure by employing ABB industrial robots. Our hypothesis was based on the argument that the 1mm robotic precision could accurately relocate the rods into a large number of positions, without the actual rods needed to bear any mechanism other than a break to hold them into position.

The IsoMachine concept

By investigating this system's articulation through various physical models it was evident that certain design and fabrication limitations had to be resolved, with the requirement for a break system to lock the rods into position while under pressure, to be the most important one, along with the optimum resolution of the grid and the requirement to control efficiently the amount of pressure applied on the polystyrene boards.

In the case of the interaction between the materials used, in order to achieve a smooth surface product, several layers of other materials had to be examined between the wooden rods and the plastic heated frame. Furthermore, one single array of rods proved insufficient to provide the demanded pressure on plastic when curvature was complex, thus two mirrored and consecutive arrays of rods had to be employed.

In addition, the robotic control of the proposed system had to be successfully utilized. The REX-Lab of the University of Innsbruck consists of three ABB robots; hence the double array of rods was not an issue. In fact both sides of the isosurface would be calibrated to their positions simultaneously by the two rear robots while the third one, with a blow-torch heating device as an extension of its arm, could heat the polystyrene board and then place it into position. Despite the relatively low heating temperature required for the polystyrene (120C), this last option was aborted due to the absence of an ABB gripper and the size of the heated plates, making it impossible to heat locally.

ISOMACHINE V1.0

The apparatus

Two plates holding 400 wooden rods on a grid of 20x20, each one consisted of three acrylic laser-cut frames, have been positioned on a wooden frame which enabled them to move towards each other by sliding on aluminium corner sectioned elements. This movement has been articulated through a series of steel wire connections, which enabled the whole system to move just by pushing or pulling a single lever. As a break system, a rubber material was in-

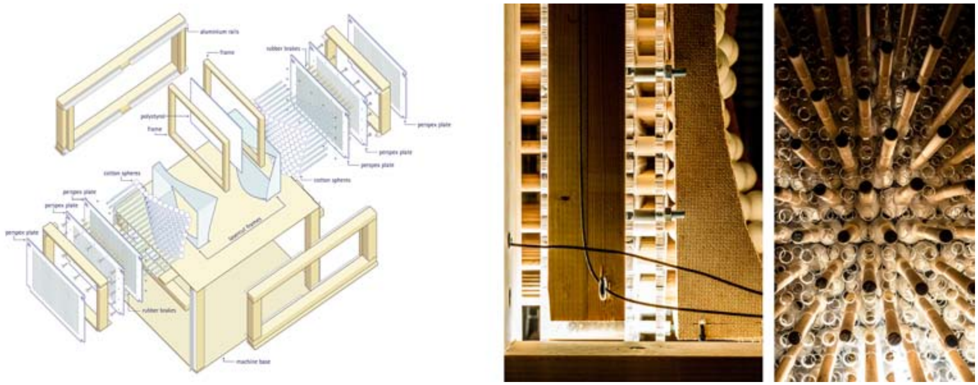


Figure 4
The Iso-Machine v1.0, exploded model and rods

Figure 5
Mirrored arrays of rods with cotton spheres at the tip, forming continuous double curved surface

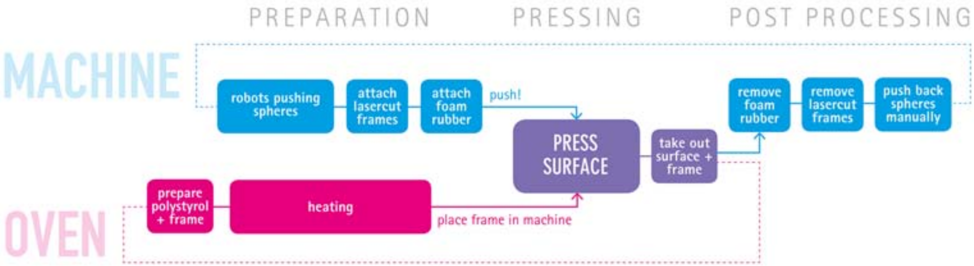


Figure 6
Procedural diagram of the fabrication stages

troduced in-between the three acrylic frames, which expanded towards the rods, when the frames were fastened together, increasing friction thus preventing them from moving under pressure (figure 4).

Finally, at the tip of each wooden rod a cotton sphere was placed, to provide a soft, flexible and heat-absorbing edge while touching the plastic and allowing the utilization of sticks on only every other grid hole, reducing the calibration time by 50%. (figure 5).

Fabrication process

Fabrication was a procedural linear process, where a set of inputs (figure 6), such as the heated plastic and the robotic calibration, lead to a controlled transformed result.

It is a rational assumption that due to the finite dimension of the material and the machine, structures larger than this size have to be tessellated in advance. Whilst the machine is calibrated by the robots, in a process that lasts about five minutes (on medium robot speed), the rigid polystyrene is being heated in an industrial oven (figure 7), for about twelve minutes. Laser-cut wooden frames ensure the preservation of the piece's outline, when the fixed on a wooden frame polystyrene plate is inserted in the machine and the lever is pushed to bring the two calibrated frames together forming the surface. The healing time of this process is about 45 to 60 seconds, providing a total fabrication time of 12 to 15 minutes per module. This compared to the 6 hours of CNC milling required for building foam-moulds added to the 16-20 hours required for the plaster to rest, proved efficient.

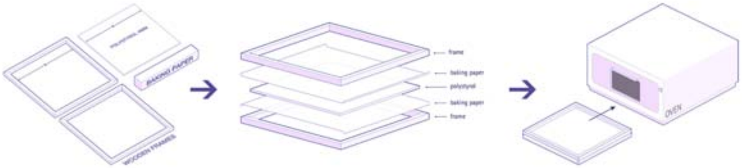


Figure 7
Heating the rigid polystyrene

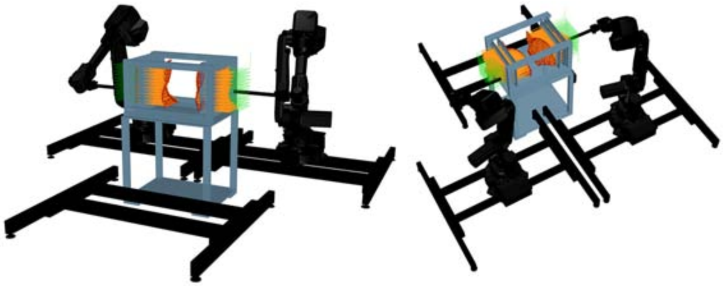


Figure 8
Snapshot of the dynamic grasshopper procedural script

Figure 9
The first case study model and material result

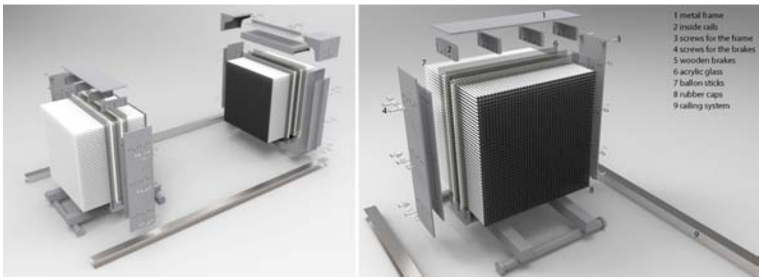


Figure 10
On the left the 2 frames (v2.0 and v2.5)exploded model, on the right the breakdown of components of v2.5.

Robotic Calibration Method v1.0

In terms of software control, a custom associative code was developed, where from one single input item, a double curved surface, the entire system automatically was recalculated, readjusting to the new parameters and then transferred as a list of commands into the robot controller. HAL [1] Grasshopper plug-in for Rhino was used, along with several other surface analysis and a few custom written components (figure 8).

The inputs are the tessellated structure's different pieces, reinforcing the initial hypothesis of a rapid prototyping approach that from one single apparatus a vast number of different configurations can be harvested. In addition a custom designed tool at the tip of the robot arm was used comprising of a straight wooden stick with a carved cavity at its edge to ensure proper fit on the rods.

First case study and results

As a case study to perform the experiment for assessment, a double iso-surface model was selected. Output data from this system can be comprised to recorded observations, the final surface outcome, cost and time management. It is evident that there is almost no material waste from this process, even in malfunctions the plate can be reheated and reused. In addition the fabrication time per piece is almost 2% of other methods. Assessing the system in terms of cost control, time efficiency, material waste management and the global character of this process, can be proved a fairly straightforward task. However, the comparison to the digital model and the effective translation and re-assembly to one unified iso-surface is rather intricate and ambiguous. Post-fabrication control and connectivity systems have to be carefully planned and examined in order to fully assess a prototyping system similar to the proposed (figure 9).

Assessment of v1.0

While the proposed system proved successful in respect to certain initial expectations, such as its global character, material waste, cost efficiency and fabrication time, it under-performed in providing an exact, in respect to the digital model, double-curved surface piece as an end product. A specific aspect in need of optimization was the resolution and size of the rods array. The more rods the more exact the curvature representation would be, and having greater rods in length would result to large curvature deviation within the same module. This requirement brought forward a period of research for a new material to replace the wooden sticks, lighter but also rigid. A choice was also made to remove the frame of the machine and reconstruct the two moving parts and connect them via a rail. A new break system also had to be designed capable of locking into position around 1600 rods at the same time.

ISO-MACHINE V2.0 & V2.5

The apparatus

The new layout consisted of two opposing frames. The first was stationed and made out of wood while the second made out of steal with a rolling system attached to its base. Each one is holding each 1600 rods made out of plastic sticks (balloon sticks bought off the market) which passed through three acrylic frames perforated on a 40x40 grid (figure 10).

In-between these three frames two wooden frames were interpolated, which moved in opposing direction via side-screws locking the rods into position, acting effectively as breaks. The new plastic rods required a rubber cup at their top to allow a smooth contact with the heated plates and avoid the melting of the plastic rods (figure 11). This grid of 40x40 rods with a maximum length of 38cm provided us with a high resolution three-dimensional dry-mould which through initial tests provided us with extremely smooth and substantially accurate results of polystyrene plates (figure 12). Yet the large amount of rods (1600 from 400 before) and their extended length (38cm from 20cm) generated a very long calibration time per surface which had to be addressed.

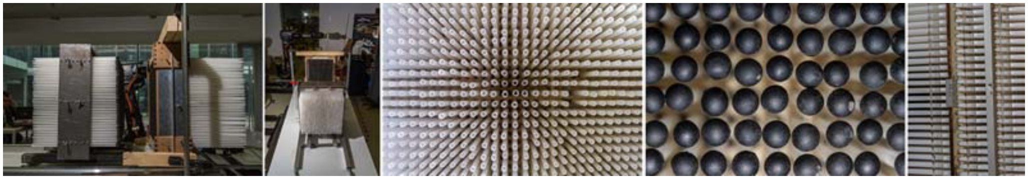


Figure 11
Elements of
IsoMachine V2.5

Figure 12
Results from
Isomachine V2.5

Robotic Calibration Method v2.0

The calibration method of the v1.0 machine was a simple 3-point based loop movement:

- starting point - robot head on zero position
- middle point -robot head on point-on-surface position
- ending point - robot head return to starting position (to avoid hitting sideways the other rods)

The above steps were repeated as many times as the number of rods. Although this worked sufficiently on v1.0 for a total amount of 600 rods (3x200 using odd and even slots alternating), the amount of point coordinates required for v2.5 was increased by 800% to 4800 (3x1600=4800). This combined with almost doubled rod length pushed the calibration time up by as much as 1500% (depending on the surface shape), which rendered the time-efficiency of our method obsolete.

To address this issue we first designed a new cross-shaped calibration-head to attach to the robot. It had four different 3D-printed edges, three being square-shaped and the fourth a simple pin-head on the size of the rods (figure 13). This allowed the robot to shift edge by rotating it's sixth-axis and also to push into average position up to 100 rods with one robot movement. Also the precision of the machine built enabled the calibration of only one frame which, if positioned face-to-face with the second, it allowed the opposing rods also to be pushed into the mirrored position.

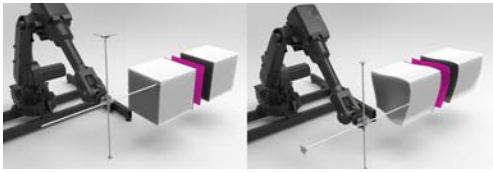
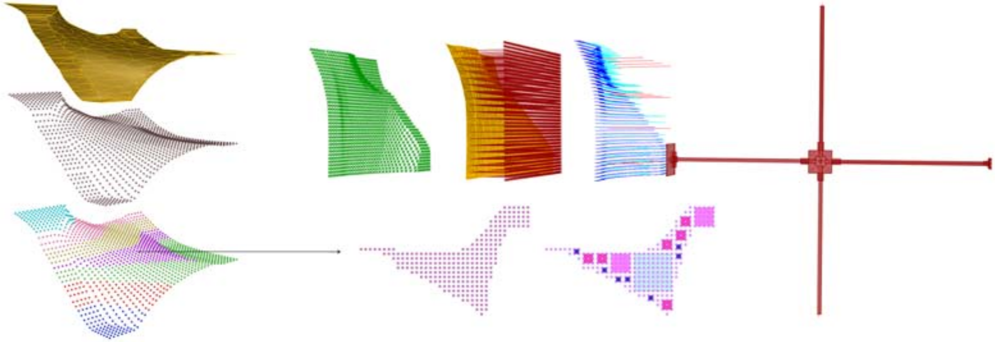


Figure 13
The new calibration method with the cross-shaped robot edge tool.

Furthermore, to effectively reduce the time of calibration via clustering, two custom routines were written within the Grasshopper3d environment based on two different basic algorithms:

- K-Means algorithm for clustering the surface points into groups based on Y-axis displacement.
- Square-packing algorithm to best fit the four edges of the cross-head to each cluster of points.

Figure 14
On the left the clustering of surface points by K-Means algorithm, bottom right the square packing of one cluster and on top right the output of the script with the line-paths ready for calibration by the robot.



The K-Means algorithm partitioned the 1600 surface points into a set range of clusters (min 5, max 10) and return the solution with the smallest overall distance the robot had to travel to reach each cluster's mean (center point) and back. This allowed the calibration of each cluster separately, reducing substantially the path the robot had to travel to avoid side-hitting the rods (figure 14).

The square packing script had as input the clusters of points returned from the K-Means algorithm. It then fit separately into each (flattened and with irregular boundary) cluster the four square sizes of the new calibration head, starting from larger to smaller. Using exhaustive search, the algorithm produced four different solutions starting from the four extreme edge points based on XZ coordinates. To speed things up, the algorithm first tested whether each point was lying in the center of a possible square by checking only whether four points existed on the corner coordinates of the square. If that was true, then the algorithm tested the whole square perimeter's coordinates for point-match. To ensure that each square's center point was also a point on the grid, it was drawn using a step value from the center, thus each square had a side length of an odd number. Therefore if the number of point-matches satisfied the following rule:

$$(2 \cdot st + 1)^2 + (2 \cdot st - 1)^2 = m \quad (1)$$

where '**st**' is the step used to build the square and '**m**' the number of matching points hits returned by the script, then the algorithm would add a square drawn from the center of the point under evaluation. From that moment on every other possible square would have to not intersect, share edge or corner points with the ones already placed.

The fact that there were always a number of remainder single points not grouped meant that the solution with the fewest squares packed wasn't always the optimum. Therefore the algorithm returned not the solution with the fewest squares, but the solution with the smallest sum of squares plus remaining points. The four new groups of squares (and their associated points) were then assigned a new common Y coordinate, which was the smallest of all points in that group, and moved to that temporary location via their respectful square-sized surfaces and using their centers as starting points. When the robot finished the first iteration of this process, it then repeated it for three more times, excluding each time the largest surface and starting with the next in line, until all rods were eventually positioned into final coordinates by the single-pin edge.

The above calibration method reduced the time needed down to a range of 8%-15% of the original required, depending on the surface under analysis. A more sophisticated algorithm, implementing better method than brute-force, with perhaps more starting points for square packing than just four corners would have reduced the time by an extra margin of 2-5%, something considered, for the scale of this research, of minimal overall effect. For that reason the whole process, via the employment of this algorithm, was considered as sufficiently optimized.

CONCLUSIONS

The level of smoothness of the produced surfaces and their curvature precision was satisfying, considering the complexity of the digital model initially set to physically build. Also the latest machine version proved very resilient to faults and breakdowns, creating the expectation that with a substantial budget invested, a larger and industrial-level machine could be produced with greater capabilities and increased precision. Yet after a long process of development a conclusion was made that as long as there's no liquid casting involved in the fabrication of double-curved surfaces, then the material properties will always define the limitations of the system. Pressuring a material to reshape it eventually increases its overall surface area while maintaining its original volume. This stretches the material to its limits, while always producing an approximation of the intended shape, never an exact replica. Furthermore, even though the increased resolution of the rods improved the smoothness of the surface curvature, the edge condition remained throughout the process problematic. And since the precise connection of one surface component to another relied on the accuracy of their edges, as the deviation from the digital model accumulated along the build-up, it eventually made the overall assemblage a challenge.

However, if the employment of this machinic system is shifted from the task of producing a large spectrum of accurate non-identical components, to that of producing a range of similar geometries, or minor variations of the same component, it could perform much better. And the proven low material waste, cost efficiency and fast production pace of this method could help in finding applications to small scale components construction, benefitting from more accurate and efficient fabrication than vacuum forming used today in the industry.

In terms of the ABB Robots used, an automation of the whole process in a way that no human input is necessary could perhaps also find applications in the industrial market. This could be achieved by constructing a large stationed grid-wall of rods on one side and by incorporating one machine frame on the robot on the other side, making it effectively an extension of its robotic arm. This way no other moving parts will be required, the robot will directly apply pressure against the grid-wall, forcing the interpolated polystyrene plates into shape, while the whole system will utilize a second robot only for calibration. This would certainly advance the fabrication process and provide a more consistent use of the robotic aided rapid IsoPrototyping methodology.

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REFERENCES

Bourke, P 2012 'Polygonising a scalar field', *www.paulbourke.net/geometry/polygonise*, Accessed 1 February 2014

Braumann, J and Brell-Cokcan, S 2013 'Robotic Forming', *RobotsinArchitecture*, http://www.robotsinarchitecture.org/ Accessed 22 June 2013
Fornes, M 2011 'nonLin/Lin Pavilion -Theverymany', *http://theverymany.com/constructs/10-frac-centre/*, Accessed 3 February 2013
Iwata, H, Yano, H, Nakaizumi, F and Kawamuri, R 2001 'Project FEELEX: Adding Haptic Surface to Graphics,', *Proceedings of SIGGRAPH 2001*
Kilian, A 2003 'Fabrication of Partially Double-Curved Surfaces out of Flat Sheet Material Through a 3D Puzzle Approach', *Connecting-Crossroads of Digital Discourse[Proceedings of the 2003 Annual Conference of the Association for Computer Aided Design In Architecture]*, pp. 75-83
Lorensen, W and Klein, H 1987, 'Marching Cubes: A High Resolution 3D Surface Construction Algorithm', *Computer Graphics*, 21(4), pp. 163-169
Zhu, H and Book, W 2006 'Digital Clay Next Generation Man-machine Interface', *International Conference on Robotics and Automation*, Orlando
[1] http://hal.thibaultschwartz.com/
[2] http://www.sawapan.eu/
[3] http://digitalsubstance.wordpress.com
[4] http://www.giuliopiacentino.com/weaverbird/