An Investigation of Robotic Incremental Sheet Metal Forming as a Method for Prototyping Parametric Architectural Skins

Ammar Kalo and Michael Jake Newsum

Abstract Given its relative low-cost, speed and versatility, incremental sheet metal forming promises to introduce new ways in which architectural sheet metal cladding components are designed, prototyped and fabricated. Expanding on research done on this fabrication method, this work aims to study Single Point Incremental Forming (SPIF) and Double-Sided Incremental Forming (DSIF) as a viable option to produce highly customized, performative architectural skins. Utilizing the reconfigurable potentials of robotic arms' versatile tooling, multi-axial positioning, and simultaneous programming, new methods are integrated into the forming process for structuring, verifying and articulating parametric parts.

Keywords Single point incremental forming · Robotic fabrication · Metal forming · Parametric design · Architectural skins

1 Introduction

Since the discovery of cast iron, metals have radically transformed the way in which architecture is built and conceived. Metal preformed under its structural capacity and physical characteristics up until the early 20th century when a shift from structural functionalism to aesthetic surfacing occurred. Once sheet metal became a staple material of a larger architectural material palette, ways to manipulate its surface became of extreme interest to architects and designers. Two dimensional

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fabrication processes have proven their efficiency in mass customization, but they limit the designed geometries to flat or developable surface topologies.

In light of these recent production methods, incremental sheet metal forming promises to be an extremely viable option to produce articulated and varied double curved surfaces for architectural cladding systems. Current incremental metal forming processes cannot compete with the speed in which stamped facade panels are produced, nor can they compete with their extreme precision and low tolerances. However, they do provide opportunities to prototype designs and produce highly variable and cost effective components. When compared with surfaces composed of multiple joined developable surfaces, the double curved geometries possible with incremental forming yield inherently self-structured panels.

The research investigates forming techniques using single point incremental forming (SPIF) and dual side incremental forming (DSIF), but also a closed loop design and fabrication process where the properties of material, the tools used and geometry are intrinsically linked. Understanding both the limits and potential of the process is essential. Through a process that encompasses digital geometric design, toolpath generation, and validation methods, designers can parametrically explore cost effective options and quickly prototype them. The different areas of exploration are always bracketed within an architectural context and viewed through the lens of contemporary methods of fabrication.

1.1 Relevance of Incremental Forming in Architecture

In 2001, Asymptote architects designed Hydra Pier which is an information center that was the first "blobby" building in the Netherlands. Its complex surface produced double curved panels which were formed using explosion forming. This technical innovation at the time was, and still is, a very tedious process of producing multiple positive and negative molds of different materials for each unique panel (Eekhout 2008). While the Hydra Pier project demanded multiple panels to be shaped uniquely in order to achieve a unified whole, the metal façade of High Line 23 designed by Neil Denari is an assembly of the same stamped panel that assembles into a tile-able pattern. Stamping sheet metal is usually associated with the automobile industry, but in this instance the architect employed this technology to gain surface variation (Simmons 2008). Incremental sheet metal forming in the near future could allow architects and designers to fabricate variable complex facade systems on large scale, whether it's a 'wrinkled' skin like Frank Gehry's New York residential tower or complex geometries with undercuts which cannot be manufactured with conventional stamping and only possible with the multi-axis freedom of an industrial robot.

Incremental forming is a currently studied as a feasible replacement for stamping, at least in the prototyping phase. The Ford Motor Company has been awarded $7.04 million by the U.S. Department of Energy to develop this technology further into a robust mass production process (http://www.at.ford.com/news/cn/Pages/

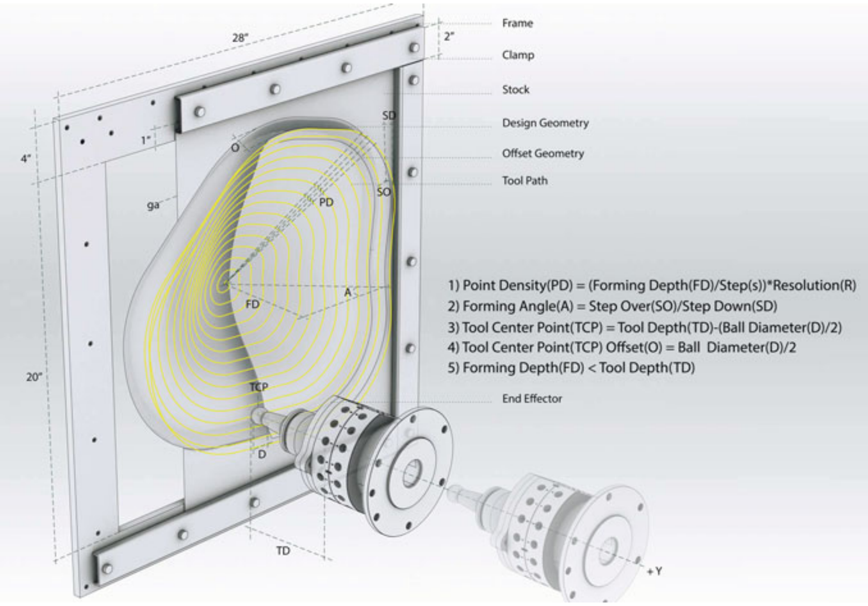


Fig. 1 Single point incremental forming with a custom forming end effector

FordDevelopsAdvancedTechnologytoRevolutionizePrototypingPersonalization LowVolumeProduction.aspx). When comparing the two processes, stamping and incremental forming, the former promises better energy savings when compared one to one in an established setup (Ingarao et al. 2012). However, for highly customized panels incremental forming becomes more efficient as it doesn't require the production of unique dies for each panel. With the process' ability to rapidly prototype and produce full-scale formed metal panels, incremental forming begs for a thorough investigation in other disciplines such as architecture and the building construction industry.

1.2 Process Overview

SPIF and DSIF are methods by which flat sheets of metal are formed creating three dimensional components with variable surface curvatures. This process of forming, unlike stamping or molding, is able to produce variety without the need of formworks or dies. A spherical forming tool, mounted on a robotic arm in this case, moves along a preprogrammed path that is generated from a 3D model. The path starts from the perimeter of the designed part and continuously pushes against the surface of the sheet metal until it reaches the center of the deepest concavity in the design (Fig. 1). Additional tools and processes have been incorporated with

SPIF, such as additional structuring tool paths or DSIF, to reduce the stock's creep from global forces while increasing the part's fidelity to the digital model.

1.3 Recent Work

Work described in this chapter is a continuation of a larger research trajectory aimed at developing the necessary tools and techniques to produce discrete parametrically designed prototypes of building skins. The work also largely builds on previous efforts that focus on computer modeling methods, parametric tool path generation, forming practices, material testing, part validation, and aggregation strategies (Kalo et al. 2014). Several materials were tested to find the limitations of the forming process and for viability. The sampling of sheet metal included cold rolled steel, aluminum, copper and brass. Cold rolled steel was used in most of the forming tests because of its high ductility and strength, which allowed for forming deeper parts. Also, previous efforts looked at integrating forming inaccuracies and springback as part of the design and fabrication process itself. Once trimmed from the rest of the stock, the formed geometry would often deform into a new relaxed shape. This release of internal forces is called springback. The deeper a panel is formed, the more it would become rigid and resist this deformation. Several design strategies, described later in the chapter, were utilized to stabilize the components pre-trimming.

2 Methods and Techniques: Single Point Incremental Forming

With SPIF, the forming limitations with one tool are that the designed geometry concavity may only be in the forming direction and the accuracy of the formed part will decrease with proximity to the perimeter. A parametric tool path allows the designer to dynamically set the resolution in terms of radial divisions and number of revolutions using a custom script written within the 3D modeling program. Bezier graph controls in the script can locally increase or reduce the resolution to compensate for uneven surface variation as well as a means of overcoming shallow forming slopes.

Most researchers, concerned with high precision forming, have used very high resolution settings in order to produce extremely refined parts. Additionally, the size of the forming stylus, or tool, plays an important role in the final surface finish. For the purposes of this research, since industrial grade tolerances and manufacturing precision is not the main goal, a medium 15 mm custom forming tool has been used. The surface 'roughness' could be predicted with percentage

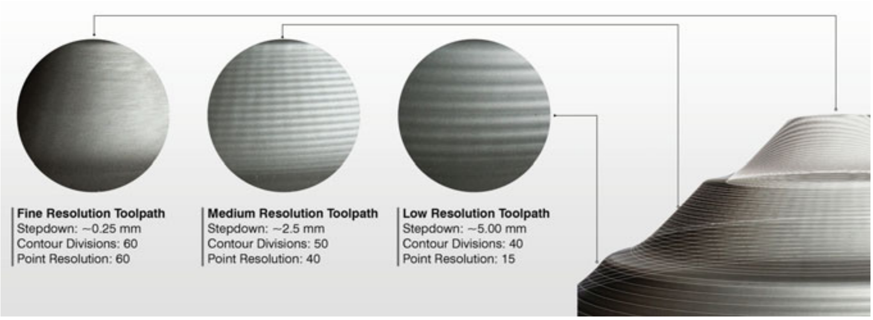


Fig. 2 Samples of the varied resolutions that can be achieved

differences that don't exceed 10 %, however, the path resolution here is treated as a design parameter that works within forming requirements in order to control surface textures (Durante et al. 2010) (Fig. 2).

2.1 Dealing with Forming Inaccuracies

In SPIF, the most inaccurate regions are usually at the 'outline' of the formed part. The metal tends to elastically deform and move the geometry along the forming axis. This occurrence is especially apparent when forming parts that meet the flat stock at sharp angles. While it is possible retain the border of the desired geometry with a backing plate or partial die, this research has been mainly aimed at investigating the potentials of a completely die-less process.

To work with the issues that arise from SPIF additional tool paths and geometric modifications were tested. Initially, the same tool path was run multiple times on the same part; a strategy that has been proven to increase forming accuracy and help to reduce the maximum deviations up to −0.5 mm (Meier et al. 2009). This increased the accuracy of the part everywhere except for the perimeter, because this region was drawn past the desired depth. Modifications to the position of the part proved to increase accuracy of the edges. Adding geometric 'skirts' to the parts' edges stiffens the geometry and provides a deeper forming condition, hence reducing the overall deviation at the edge (Kreimeier et al. 2011).

Additional tool paths were tested other than the spirals. A zig-zag tool path method not only reveals where the actual part is on the panel but also draws the metal deeper and more consistently. The identifiable outline could be used to easily register the geometry for a secondary process such as trimming and panel registration (Fig. 3). When conventional secondary passes (spirals) were used, the outer portion of the geometry is formed while the center is moved inward leaving it touched with much less force by the forming tool. Since the zig-zag moves across the formed geometry linearly instead of radially, the center of the formed is

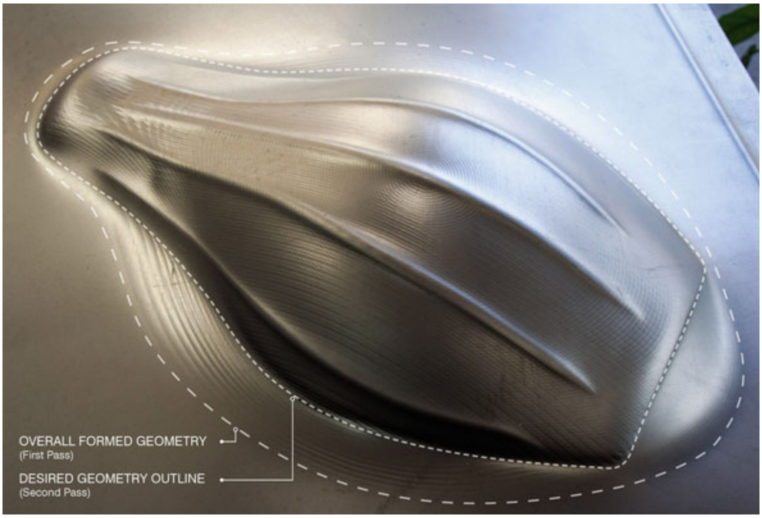


Fig. 3 A refined part with overlapping spiral and linear toolpaths

not isolated by newly formed material, thus allowing the center to maintain its position relative to the forming tool which allows the forming tool to maintain contact with the material. The contrasting grain also provides a unique aesthetic pattern that could be exploited as part of the component design (Fig. 3).

2.2 *Laser Scanning*

While precise articulation of the formed parts can be achieved by running the same toolpath multiple times, their accuracy could only be determined by a digital scanning method. With the addition of a scanned digital representation of the formed part, the increase in accuracy of each pass could help validate forming results and detect slight variations in the geometry.

For the scanning routine, the robot is programmed to move to fixed points along a tool path and shoot a laser point at each position. When the tool is at the approximate center of its range, a voltage reading from -1 to -10 V is then converted to a range coordinate in millimeters and an XYZ position. All the information gathered from this process is stored in a separate file. The data files are then used as inputs in a custom script that redraws the toolpath to displays any deviations between the forming and scanning toolpath. It also shows where the formed parts are in relation to the digital model (Fig. 4). The scanning results for a test panel formed by SPIF (shown below) reveal a minimum deviation of 0.008 mm at the center of the part and as maximum of 13.75 mm at the edges.

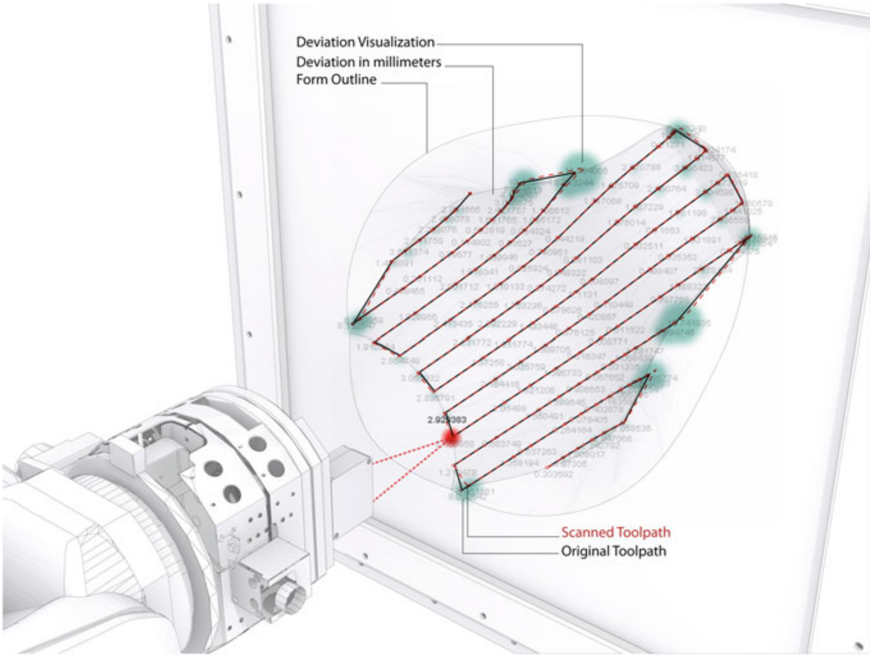


Fig. 4 A diagrammatic demonstration of the laser scanning process

This system is still currently being tested for repeatability and the effect of different surface angles on the laser sensor readings.

The model produced by the scanning process is then used for additional processes after the primary forming. It accurately locates where detailed passes should be positioned. The model is also measured at the edge of the designed part to verify and reconstruct a tool path for cutting the material from the stock sheet.

3 Dual Side Incremental Forming

Moving on from SPIF forming to DSIF presents a set of new challenges that couldn't be succumbed without the invaluable knowledge acquired from SPIF. Forming panels that have positive and negative Gaussian curvatures or rapid slope variations is very difficult using SPIF, however with DSIF there's more control and freedom over geometries that can be formed. Two different types of DSIF were employed and developed as the research moved forward (Fig. 5).

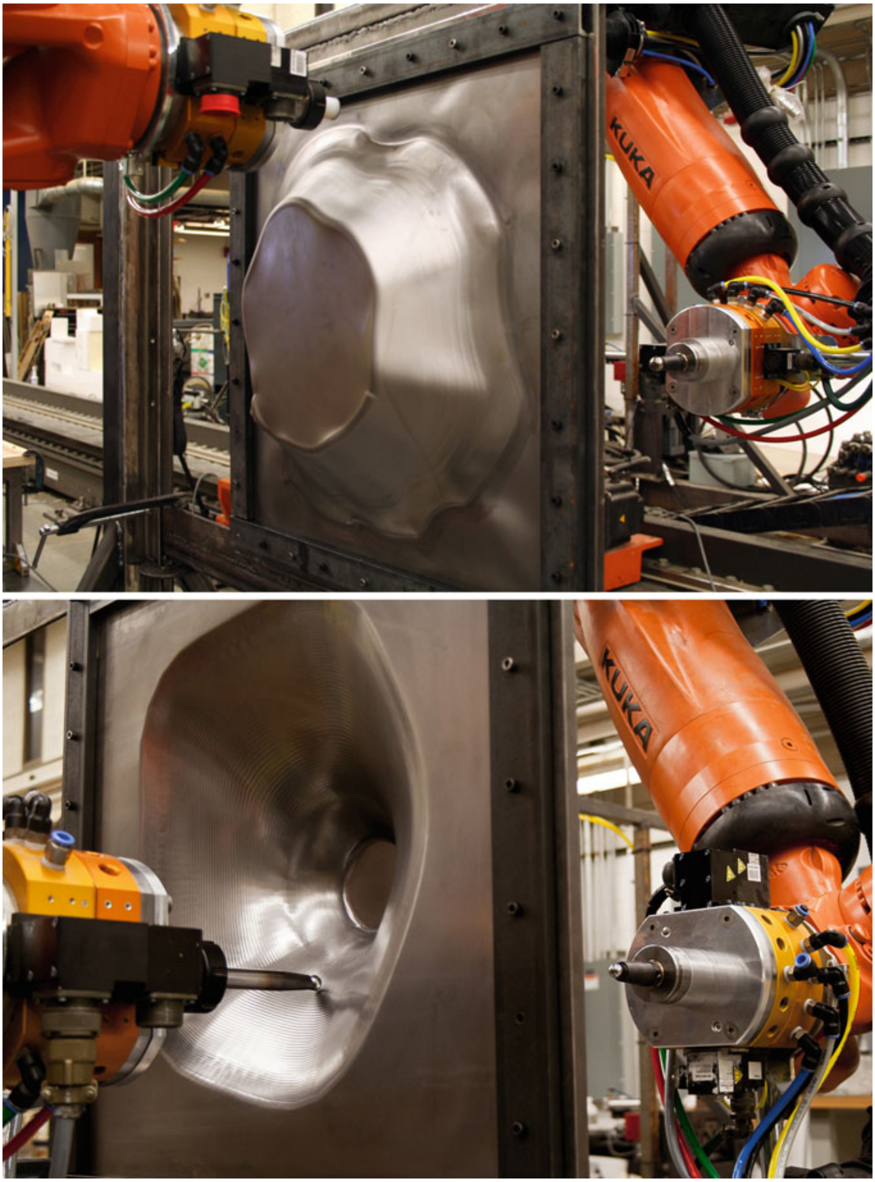


Fig. 5 *Top* DSIF Method A with a forming tool and a support tool. *Bottom* DSIF Method B with two forming tools

3.1 DSIF Method A: Forming Tool + Support Tool

This method requires programming a tool to continuously follow the perimeter of the form on the back side of the stock to stop the material from globally deflecting and moving the part along the forming axis. Constantly articulating the perimeter reduces forming inaccuracies at the edge even when there is a steep slope. This method eliminates the need for a backing plate with a cut-out to retain the 'flatness' of the stock at the formed parts' edges. A machined flat Delrin rod is used to fabricate this tool. Moving smoothly across the back side of the metal with low friction, the thermoplastic cylinder can resist forming pressures and prevent geometric creep (Fig. 5).

3.2 DSIF Method B: Forming Tool + Another Forming Tool

In order to support the material at each point in the forming process, a forming tool may be used from both sides of the material at the same contact point. When the forming tools are compressing the material at the points of contact, the accuracy and stability of the formed part are greatly increased (Malhotra et al. 2011). Laser scans of the perimeter show an averaging of the amount of deviation along the whole perimeter in DSIF whereas the deviation in SPIF shows significant fluctuation depending on the geometry as indicated in Fig. 6. Currently, the contact of both forming tools occurs during the beginning of the spiral. The gap between the two forming tools is determined by the sine law which has proven to inaccurately describe the material thickness causing the outer forming tool to deviate from the surface and eventually lose contact (Malhotra et al. 2011).

With SPIF, the generation of the tool paths is simple. The center points of the tool can be found by offsetting the designed surface by the radius of the tool and generating the forming spiral. With two tools, one cannot simply offset the surface in both directions, because the points along the spiral would not have been produced in a way that shares a contact point.

Toolpaths for this DSIF method are produced by calculating two separate tool center points that share a point of contact on the material. The tools' series of contact points must first be constructed to then find the positive and negative normal vectors from each point along the surface. Calculating the coordinated center points of the forming tools ensures that the two spherical tools stay tangent to each other along specific vectors (Maidagan et al. 2007) (Fig. 7).

The vector between the two forming tools can be modified to direct forces at the contact point if the material thickness is accurately calculated. The normal vector is the maximum angle off of the primary direction of the draw when forming. This process of constructing positions for DSIF is commonly used as it is a reliable method. The design of the spiral, through the use of Bezier graphed divisions,

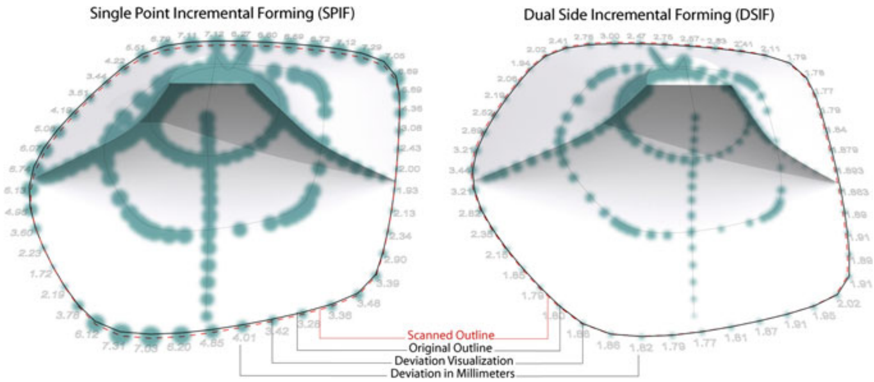


Fig. 6 Comparison showing edge and overall deviation between SPIF and DSIF

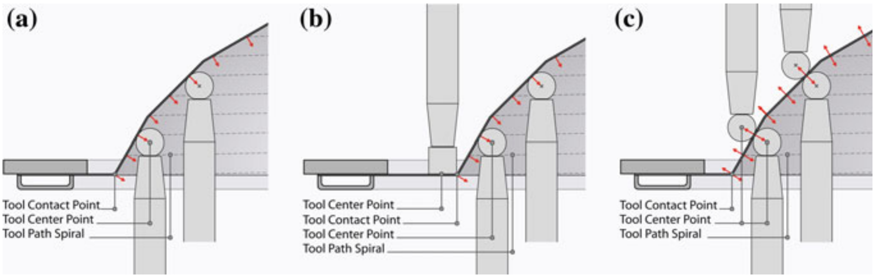


Fig. 7 **a** SPIF. **b** DSIF Method A. **c** DSIF Method B

allows for the forming process to be customized as an aesthetic and functional calibration of the spirals' density throughout the tool paths.

Pairs of points for each move of the robots are synced at every position through synchronous programming using KUKA Roboteam. Producing tools paths for more complex surfaces with both convexities and concavities has not been fully developed at this point in time due to the multiplicity of new factors that are introduced with DSIF. In the future, the ability to do so will open up the possibilities to produce more varied and topologically different panels.

4 Prototypes and Applications

Several proof of concept prototypes were produced as part of this research to demonstrate potential application of incrementally formed architectural skin components. A self-structured thickened porous skin was developed by forming multiple varied bell shaped components that change in size according to the

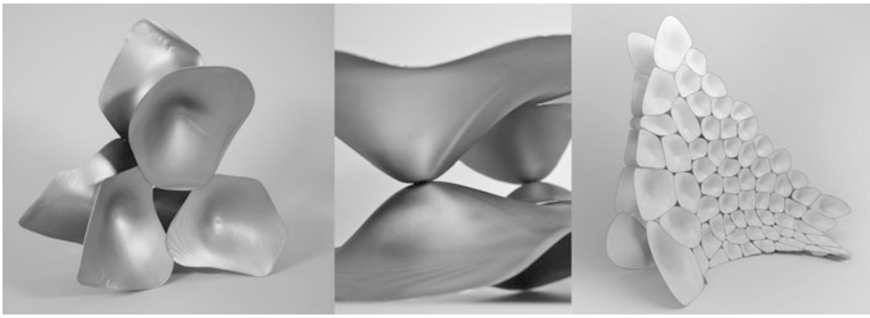


Fig. 8 Aggregation of self-supporting thickened porous skin

overall geometry curvature. The parts were spot welded together at the valleys and peaks to create the self-supporting system (Fig. 8).

Another system was developed as a series of panels that have a global pattern of ribs which structure the edge and register the panels through overlapping connections. The central protrusions are formed as undercuts (easily achievable with multi-axis forming) and orient the panel on a clipping system (Fig. 9). The bespoke ribs, bumps, and surface textures aren't formed solely on their aesthetic value, but are born out of the conflation of design, fabrication process, and connection detailing. In addition, they deliver a performative relationship between the panels and the materials formed (Hensel and Menges 2009). The aim is to avoid any kind of superficial patterning and allow for the expression of the performative aspects embedded in the panels. These patterns were a result of trying to find a design solution to minimize springback after trimming and utilized as indexing guides. A series of different structural patterns based on surface curvature analysis were developed and tested. Laser scanned models of the 'ribbed' trimmed panels show a 75 % improvement in the overall geometry when compared with untreated panels. The amount of deviation drops from 73 mm on the original un-textured panel to 15 mm after introducing the structuring textures (Fig. 10).

Another area of added functionality was geared towards developing panels that collect and direct water. The Namib Desert Darkling Beetle has the unique ability to 'fog-bask', a strategy utilized by the beetle to use its own body as fog collectors (Nørgaard and Marie 2010). Similar to the Namib Desert Darkling Beetles' elytra, the panels are designed to have areas coated with a hydrophilic, water attracting, film and other areas with a hydrophobic, water repellent, film.

The implication is creating a building facade or roof systems that employ such a technique to efficiently collect water from fog. For this strategy, 'micro bumps' are added to the formed component to increase the surface area. The hydrophilic peaks of the bumps allow the water to gather and then drip across the hydrophobic once it reaches its capacity. The surface texture not only structures the panel locally, but also become guiding flow-lines for shedding water in a controlled way. This system has been tested on small samples and is yet to be developed into a larger aggregated system (Fig. 11).

Fig. 9 A component with performative textures and features

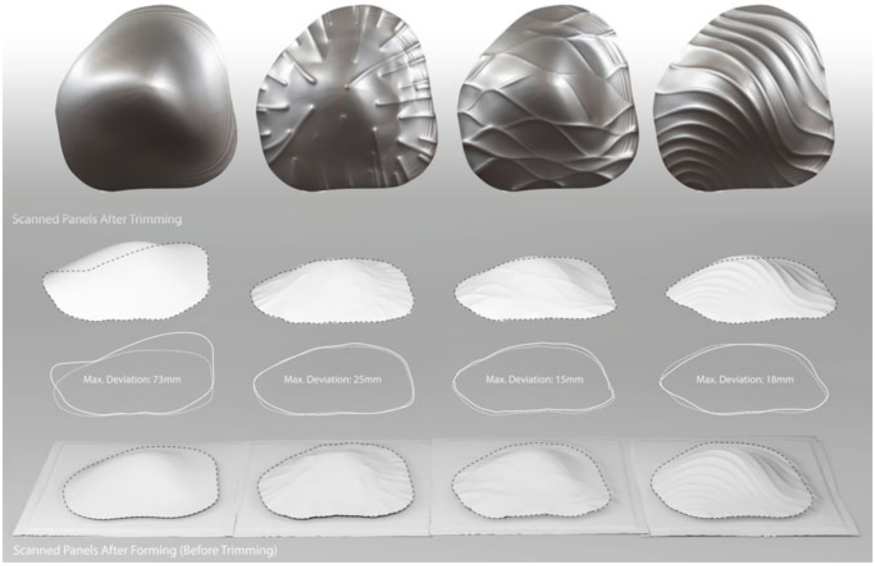


Fig. 10 Comparison of overall geometric improvements with the 'ribbing' system

Fig. 11 Prototype of a textured performative water shedding surface

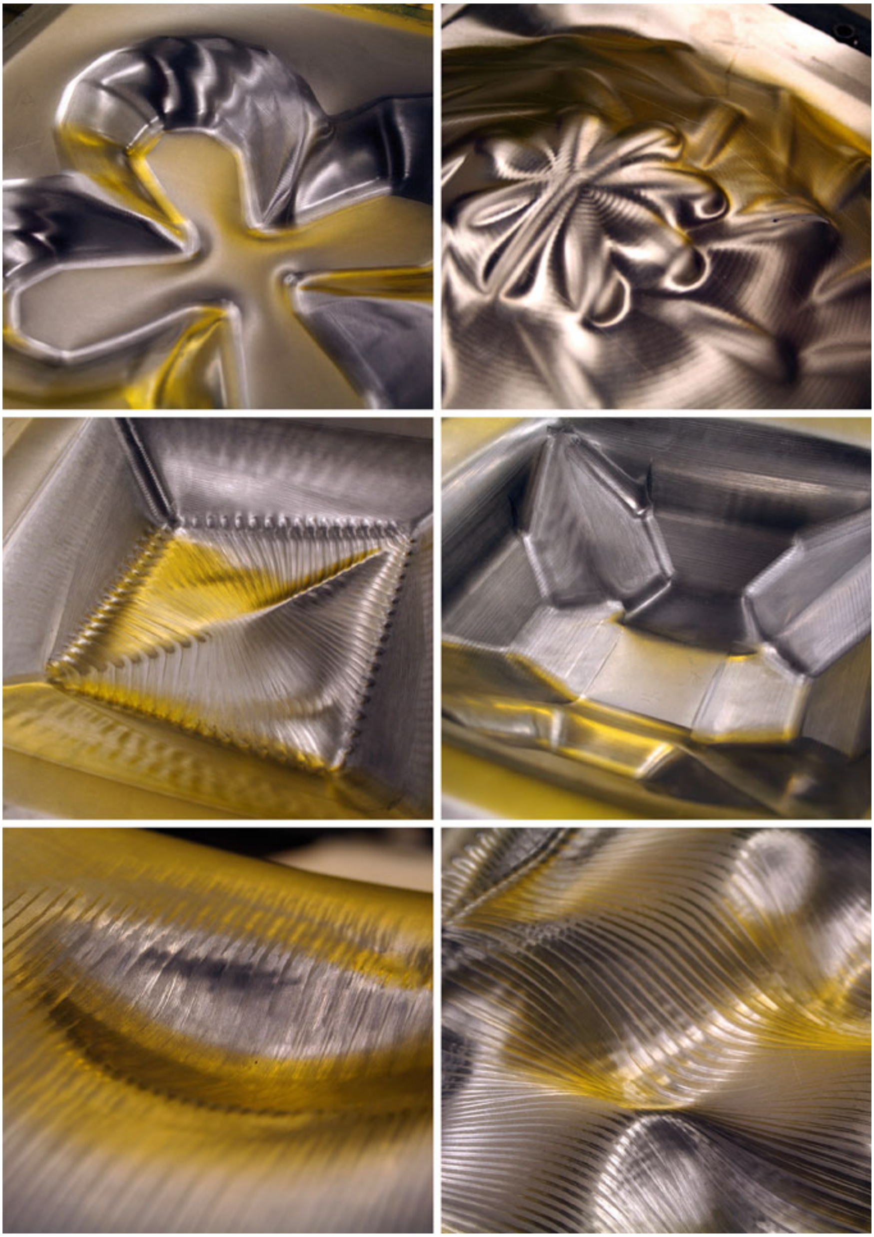
5 Conclusion

Most of the objectives in this phase of the research have been completed. Those include refining tool path generation, finding ways to incorporate forming inaccuracies in the design process, as well as developing a scanning and validation process to assist in forming secondary design and performative features. Developing a more robust double-sided forming process hasn't been fully achieved and is currently under development.

Given its low-cost and versatility, incremental sheet metal forming promises to radicalize the ways in which architectural sheet metal panels are designed, prototyped and fabricated. While this forming method's relative speed and efficiency is effective in the prototyping phase or for low-volume production, it still cannot compete with the high production speeds and precision of other contemporary metal forming processes.

Architectural precedents mentioned earlier serve an important starting point for developing such panels and enable an avenue to scrutinize existing paneling systems and study ways in which they could be advanced with a fabrication process like incremental sheet metal forming. The skins developed as part of this research were means to refine the process and its techniques rather than design fully fledged systems. Future research will utilize the knowledge gained from these studies to further advance and refine the process as well as investigate new possible types of performative aggregated cladding elements in a building envelope.

In conclusion, incremental sheet metal forming, in all its current variations, provides a unique opportunity to investigate new forms of architectural expression through performative varied façade systems. This research refines a closed loop method for an integrated computational design and fabrication process for incremental sheet metal forming as a means to produce low-cost parametrically customized aggregations of architectural skins.



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