ROBOTIC FORMING

Rapidly generating 3D forms and structures through incremental forming

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Abstract. The past years have seen significant developments in the area of robotic design interfaces. Building upon visual programming environments, these interfaces now allow the creative industry to define even complex fabrication processes in an easy, accessible way, while providing instant, production-immanent feedback. However, while these software tools greatly speed up the programming of robotic arms, many processes are still inherently slow: Subtractive processes need to remove a large amount of material with comparably small tools, while additive processes are limited by the speed of the extruder and the properties of the extruded material. In this research we present a new method for incrementally shaping transparent polymer materials with a robotic arm, without requiring heat or dies for deep-drawing, thus allowing us to rapidly fabricate individual panels within a minimum of time.

Keywords. Incremental forming; robotic fabrication; visual programming.
1. Introduction

Complex geometries in architecture and individual free-form-facades are becoming increasingly prominent in the urban landscape. While new digital tools greatly facilitate the efficient development and segmentation of these complex architectural structures in the design phase, the actual production of free-form-elements is still laborious and expensive. Common methods such as deep-drawing of plastics (e.g. Kunsthalle Graz) or explosion forming of metal (e.g. Hydra Pier, Haarlemmermeer) are based on the fabrication of individual dies for every unique surface geometry (Brell-Cokcan and Braumann, 2013). While dies can be re-used in the serial fabrication of identical elements, relying on such processes for single, individual pieces is highly time consuming and material-intensive.

Therefore, we are exploring the fabrication strategy of Single Point Incremental Forming (SPIF) within the context of individualized production, towards enabling the fabrication of highly customized, transparent elements.

2. Investigation

So far, SPIF has mostly been explored in the context of mechanical engineering and material science (Jackson and Alwood, 2009), though more recently also by researchers in architecture, who focused on the development of tools and techniques for the parametric design of prototypical, metal building skins (Kalo and Newsum, 2014). Our investigation into SPIF is focused on the practical applicability of the SPIF process to the working practices of the creative industry and other groups with less experience in automated production planning. Furthermore, we place a special importance on realizing a continuous design to production workflow, utilizing visual programming strategies that are now commonly used in the creative sector. Thus, we implemented the necessary process immanent steps in the digital design environment of Rhino and Grasshopper, allowing us to quickly prototype the process in both physical and virtual space.

While the initial material research was done in the laboratory, our investigations into the practical applicability of such processes involved a series of intensive workshops, where participants intuitively explored material and digital constraints of the process and created a series of exhibition pieces (Fig. 1). Our developed process was also featured as part of the Ars Electronica Festival - one of the world’s most significant digital media festivals - with the goal of demonstrating how industrial machines and industrial processes are no longer exclusive to industrial mass-fabrication, but can be manipulated and re-applied by the creative industry. A Leap Motion 3D-scanner allowed members of the audience to interact in an intuitive way with the par-
ametric design and fabrication model running within Grasshopper. The hand movement detected by the sensor was linked to the design parameters of position, depth and size of the deformation shape, continuously morphing the geometry and fabrication toolpaths in real-time (Fig. 2). As a subsequent step, an agent system explored the generated 3D-surface in the design process creating a spline like pattern that emphasizes the spatial properties of the panel structure (Fig. 2). This pattern was implemented during manufacturing as additional paint layer on one side of the polymer sheet.

![Image](image_url)

**Figure 1.** Geometries intuitively generated through SPIF: Haptics of deformation paths (left), twisting of sheet through distinct deformation (middle), double sided deformation (right).

<table>
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<tr>
<th>1 - SHAPE BY LEAP MOTION</th>
<th>2 - PATTERN BY AGENT SYSTEM</th>
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<tbody>
<tr>
<td>Positioning of spheres based on 3D scanned hand motion</td>
<td>Calculation of spline pattern by agent system</td>
</tr>
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![Image](image_url)

**Figure 2.** Intuitive toolpath generation through a combination of leap motion scanning (step 1) and an agent system (step 2).
3. Single point incremental forming of polymer sheets

SPIF is a cold-forming production process which is capable of manufacturing arbitrary free-form-surfaces by gradually pressing sheet material into the desired shape with a spherical tool attached to a robotic arm or CNC machine (Fig. 3). In comparison to commonly used hot-forming processes such as deep drawing, the deformation is achieved in a single production sequence not requiring dies or other preliminaries. Therefore, the application of SPIF is most interesting for the efficient and rapid production of small batch sizes of individual, prototypical items (Tuomi and Lamminen, 2004) or a great number of diverse elements such as façade panels.

![Figure 3. SPIF of a transparent polymer sheet. Stress micro-fractures are visible.](image)

The technique was initially developed for metal sheets, but has more recently also been applied for polymer sheets (Franzen et al, 2009). Our research is focused on applications of transparent polyethylene terephthalate (PET), which offers a range of benefits for the creative industry. The main advantage is the polymers low yielding strength which leads to a smaller expenditure of force during deformation and thereby to a decreasing process energy consumption. Furthermore the optic behaviour of the transparency panels can be adapted and implemented as a design strategy e.g. via grinding or painting - using the same robotic setup but with different attached tools. Towards the realization and assembly of actual building elements, the light weight of the polymer panels becomes another advantage which greatly facilitates on-site assembly.
4. Workshop setup

Our investigation into SPIF was conducted using the depicted setup (Fig. 4) with the main elements being an industrial robot as well as a metal frame holding the polymer sheet. Furthermore, a range of different sizes of tools and sheets were utilized for the different workshops (Table 1). The layout and position of the frame as well as the deployment of robotic arms were chosen in order to offer a variation of the tool angle as well as enable double sided editing of the sheets using only one robot - thereby being able to realize a light-weight, locally flexible and less expansive workspace.

![Figure 4. Low-payload KUKA Agilus robot deforming a transparent PET sheet (left). Section of double sided deformation setup (1-Frame, 2-Sheet, 3+4-One robot deforming both sides one after the other , 5-End effector with deformation and painting tool).](image)

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<tr>
<th>W1</th>
<th>W2</th>
<th>W3</th>
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</thead>
<tbody>
<tr>
<td><strong>Robot</strong></td>
<td>Kuka Agilus (6kg payload)</td>
<td>Kuka Agilus (6kg payload)</td>
</tr>
<tr>
<td><strong>Sheet Size</strong></td>
<td>250 x 250 mm</td>
<td>300 x 300 mm</td>
</tr>
<tr>
<td><strong>Tool Size</strong></td>
<td>Ø 8 mm</td>
<td>Ø 8 mm</td>
</tr>
<tr>
<td><strong>Special Effects</strong></td>
<td>Shading via grinding, drilling</td>
<td>Shading via grinding, illumination</td>
</tr>
</tbody>
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The double sided editing enables the production of complex forms within a single process step without changing the main setup e.g. through turning over the sheet, and without the need for supporting systems. Additionally, the combination of design strategies and visual properties allows a more complex arrangement of foreground and background or the superimposition of form and pattern or the application of post processing work on both sides of the sheet.
5. Process analysis

5.1. DESIGN AND PRODUCTION WORKFLOW

The research as well as the individual workshops started out with intuitively collecting design ideas, patterns and shapes without yet considering the production process. Afterwards, these ideas were transferred to a digital 3D model in Rhino or Grasshopper and finally used to inform tool paths using basic and easily learnable geometric operations with Grasshopper. Afterwards, the design and manufacturing processes were linked by converting the paths into machine code using KUKA|prc and sending the resulting data via Ethernet to the robot (Braumann and Brell-Cokcan, 2014). Finally, the sheets were deformed by the robotic arm.

Each of these steps take up a very short amount of time and can be easily adjusted and fine-tuned by changing the input variables of the parametric definition. Especially, the actual deformation processing time is very low, which coincidently leads to a decreasing energy consumption and a greater economic efficiency of SPIF (Dittrich et al, 2012). With ongoing research and more preset tools within Grasshopper and KUKA|prc, the design and prefabrication planning is further reduced to a minimum of necessary work time consumption, which is one of the important factors for a successful application of the process next.

5.2. PATH PLANNING AND SHEET DEFORMATION

Path planning has got a great influence on the haptics of the final shape as well as the production time and general feasibility of forms. During the workshops, two approaches have been favored for path planning - either by slicing the 3D shapes in horizontal segments – similar to subtractive processes such as contour milling with a constant stepdown - or by manipulating the dimensions of linear patterns in 3D-space – alike contour milling with a three-dimensional stepdown according to the shape’s deviation (Fig. 5). However, especially when working with polymer sheets, the path planning strategy not only affects the local area immediately next to the forming tool, but also has a significant impact on the global sheet geometry. Our research showed that even small, superficial deformations can generate a twisting of the polymer sheets (Fig. 1, middle). As this effect cannot yet be considered using our current evaluation and simulation tools, the twisting effect creates an increasing difference between the digital model and the physical panel that can cause unpredictable collisions. Still, these effects can also be used on purpose as a design strategy in order to create new geometric panel shapes with a minimum of deformation action.
5.3. CONTINUOUS DESIGN

Due to the short manufacturing cycle, SPIF is most suitable for rapid design-to-production workflows (Tuomi and Lamminen, 2004), to which parametric and adaptive planning as well as rapid learning and improvement techniques can be seamlessly added. The depicted process confirms the application of a closed, at any time digitally controllable workflow from the design idea to the final product. Through the constant evaluation of the gained elements, prompt optimization can be added to the process procedure. Accordingly, an increase in the efficiency of the building industry - including designers, engineers and prefabrication specialist – can be achieved.

More than that, SPIF is capable of expanding its application to the whole lifecycle of the produced (building) element, which is caused by the deformation process itself. Since no additional help (heat, dies) other than the pressure of the tool is necessary to generate the shape, the polymer sheets can be restructured at any time. Accordingly, a total reshaping to the original state of a planar sheet was already experimentally proven with SPIF of metal sheets (Takano et al., 2008) and will be further examined for polymer sheets in future research.

Thus, there is no final state of neither the element nor to the manufacturing procedure. Overall, this fact is reinventing the design thinking and making to be crucially relevant at all planning and utilization stages to the products very final end of life - experiencing initial design concepts, as well as designing for reshaping, reusing and recirculation of each object. However, the ongoing design and fabrication work is not bound to certain skilled per- 

![Figure 5. Different path-planning strategies for incremental sheet forming.](image-url)
sonnel but to any involved person during the products life cycle on account of the relative simplicity of the SPIF procedure. Therefore, the contemporary interest in intuitively fabricating products with individual, adaptable character is not only a prelaminar decision but still inextricably inherit and long lastingly embedded in the physical status of the element itself.

6. Product outlook

6.1. TRANSPARENCY OF MATERIAL

Working with transparent material opens up new challenges in regards to the surface finish, but also leads to entirely new effects, such as the intricate light patterns (Fig. 6) created by the reflected and refracted light shining through 3D surfaces. The computational design of caustics is already being researched (Kieser et al, 2012) but needs to be adjusted for this specific production process. We see a wide range of applications for such panels, from interior design to entire façade structures with additional organic solar cell systems or integrated, individualized shading structures.

![Figure 6. Light-patterns: Combination of deformation and paint pattern (left) and pattern like shade only through deformation (right).](image)

6.2. SCALABILITY

For a widespread application of any manufacturing procedure within the architectural context, the scalability of the product and process is mandatory in order to react on the different needs of design and planning stages – model, building element and building. For verification, the SPIF process was applied to different sizes of experimental setups including differences in the machinery as well as the size of polymer sheets (Table 1).

These results show that the process is inherently scalable, using robots with higher payload and greater range enables the processing of larger, thicker PET panels. Due to the parametric nature of our code, we can rapidly adjust the process to new material and mechanic constraints, adapting the
toolpaths to fit the particular combination of machine and material. The required tools are also mechanically simple, consisting only of a metal pin with a (semi)-circular tip mounted on a bearing system. Thus, even the haptics of the toolpath are easily scalable by quickly replacing the tools.

6.3. MATERIAL CHALLENGES

Due to the material characteristic of polymer sheets, the sheet was prone to spring back during deformation, which as a result negatively influenced the accuracy of the designed shapes (Franzen et al, 2008). Although this might have interesting aesthetic effects, the path planning needs to be globally adjusted according to the individual behavior of different polymers and their specific spring back factor in order to meet the legal requirements of tolerances in the building sector. Considering that, research was undertaken for various metal deformation (Behera et al, 2012) as well as simple geometric shapes of polymer sheets (Le, 2009). The next step is to adapt these research results to be able to calculate most diverse irregular forms of polymer sheets for manifold application.

7. Conclusion

Today, multi-functional robotic arms and visual programming strategies allow architects and designers to develop entirely new fabrication strategies within a comparably short timeframe, creating new products and workflows that are optimized for the requirements of the creative industry.

Our research shows the potential of the incremental forming of transparent polymer sheets as a highly flexible, scalable fabrication process that can be used for large-scale architectural applications. We see particular promise in the emerged topic of illumination effects, towards using SPIF made facade panels for light guidance and targeted shading. Therefore, experiments on optics, refraction and light control are upcoming.

Moreover, we believe that the continuous design approach of SPIF allows for an efficient customization of building elements in full 1:1 scale. Thus, future research will focus on the potentials and constraints of implementing the procedure onto building sites. We expect that the on-site, just in time fabrication of panels, can allow us to individually minimize building tolerances. Furthermore, the process as well as the design of the facade panels can be adjusted according to on-site detected changes in constraints or other environmental influences.

On a broader outlook, research on alternative fabrication processes such as SPIF contribute to the implementation of new strategies for the integration of design and production during the whole lifecycle of building elements and
thereby strengthen the longevity and environmental impact of buildings in general, although the underlying building materials are not yet classified as sustainable.

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References