Artistic computational design featuring imprecision

A method supporting digital and physical explorations of esthetic features in robotic single-point incremental forming of polymer sheets

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Design strategies that employ digital and material imprecision to achieve esthetic innovation exhibit high potential to transform the current precision-oriented practices of computation and digital fabrication in architecture. However, such strategies are still in their infancy. We present a design method facilitating intentionally-imprecise esthetic explorations within the framework of digital design and robotic single-point incremental forming. Our method gives access to the esthetic fine-tuning of molds from which architectural objects are cast. Semi-precise computational operations of extending, limiting, deepening and shallowing the geometrical deformations of the mold through robot toolpath fine-tuning are enabled by a digital toolkit featuring parametric modeling, surface curvature analyses, photogrammetry, digital photography and bitmap image retouching and painting. Our method demonstrates the shift of focus from geometric accuracy and control of material behaviors towards intentionally-imprecise digital explorations that yield novel esthetic features of architectural designs. By demonstrating the results of applying our method in the context of an exploration-driven design process, we argue that imprecision can be equally valid to accuracy, opening a vast, excitingly unknown territory for material-mediated esthetic explorations within digital fabrication. Such explorations can interestingly alter the esthetic canons and computational design methods of digital architecture in the nearest future.

Keywords: *Artistic architectural design, artistic digital crafting, creative robotics, material agency, fabrication inaccuracies, robotic single-point incremental forming of polymers*

BACKGROUND

High precision of the digital process and its physical result has been the main target of mainstream computational design research and practice in architecture. The majority of the work focused on developing computational means of simulation, prediction and real-time monitoring of material behaviors during fabrication (Menges 2015; Sheil 2014), to derive physical results that are as close as possible to digital model representations.

Recently, however, a different approach has been proposed; one that purposefully introduces imprecision into the computational process to obtain designs whose infidelity is an esthetic virtue. Single research efforts appeared in this context, such as the studies in experimental 3D printing that explore intentional tweaking of the process to produce erroneous esthetic features in the printed objects (Atwood 2012; Gürsoy 2018; Mohite, Kochneva and Kotnik 2017). Most lately, a more collective effort to advance knowledge has been the ACADIA 2018 conference, featuring the theme: "Recalibration: On Imprecision and Infidelity".

The conference chairs, in a series of manifestoes, advocated that being deliberately imprecise in computation can lead to inspiring advances in architectural esthetics (Kobayashi & Slocum, 2018). More specifically, that intentionally-flawed digital processes, such as glitching, messy programming, simplified iteration, trial and error- and chance-based operations, can yield new typologies of form, surface and texture (Anzalone, Del Signore and Wit 2018a). The chairs also argued that such digital design approaches, repositioning computational design at the intersection of art and technology, can renew the interest of architects in more spontaneous artistic practices, liberated from the convention of ultimate precision (Anzalone, Del Signore and Wit 2018b).

Despite its potential to revive the mainstream practices of computational design and digital fabrication, this strand of research is still in its infancy, as indicated by a low number of publications on the subject. The first steps to advance knowledge have been taken, but a fully established generation of novel digital design practices celebrating imprecision is yet to emerge. In light of this challenge, this research study contributes with a digital design method deliberately featuring imprecision to facilitate esthetic explorations of emergent design features in a fabrication process of robotic single-point incremental forming (SPIF).

STATE OF ARCHITECTURAL RESEARCH ON ROBOTIC SPIF

Extending the role of imprecision in robotic SPIF is important from the standpoint of knowledge advances in digital fabrication in architecture. Firstly, because research so far has been focused on developing methods that increase precision and geometric accuracy (Kalo and Newsum 2014; Nicholas et al. 2016). To our knowledge, no published methods exist that engage with the inaccuracies in SPIF for creative, esthetic purposes. Only one study briefly mentioned that the imperfections in the form of microcracking of incrementally formed polymer elements could be an interesting design generator (Lublasser et al. 2016). However, this remark was not further elaborated on in the mentioned study due to a different research focus.

The second reason motivating our research relates to the scope of knowledge on materials used in architectural SPIF. So far, the majority of studies have focused on SPIF of metal sheets while knowledge on architectural forming of polymers is limited. SPIF of polymers is interesting from the imprecision standpoint due to their lower stiffness in comparison with metals, which results in a potentially wider range of imperfections occurring in the formed object (Franzen et al. 2008). New studies are therefore needed which explore how this higher degree of forming inaccuracy affects the esthetic exploration potentials.

Thirdly, the previous research on architectural SPIF embraced its employment to produce smaller architectural elements, assembled to form larger structures, such as façades, roofs or flooring (Kalo and

Newsum 2014; Nicholas et al. 2016). New studies are needed that explore other architectural applications of SPIF, such as in the production of molds used for casting architectural elements from other materials.

RESEARCH CHALLENGE AND AIMS

Prompted by the above challenges within the current state of the art, we set out to determine how the traditionally precision-focused computational design process can accommodate imprecision to enable deliberately inaccurate explorations of esthetic features arising from the inaccuracies of the SPIF process. The introduction of deliberate inaccuracy into the process was driven by design-oriented premises. Our goal was to demonstrate the positive effects of allowing partially unpredictable material behaviors to affect the esthetic appearance of the final design.

To reach this goal, we established the following research aims. Firstly, to compose a set of digital media enabling computational design explorations featuring imprecision and intuitive artistic design explorations. Secondly, to develop visual programming scripts allowing for intentionally-imprecise modifications of object geometries for the purpose of creative explorations of geometric inaccuracies of polymer sheet SPIF carried out using a robot. Thirdly, to provide an example of a design object whose features are iterated using our method and to discuss the esthetic implications of our method application.

RESEARCH METHODOLOGY AND DESIGN

Our research design combined the elements of artistic architectural research (Dyrssén 2011) and architectural research-through-design (Dunin-Woyseth and Nilsson 2008). Such a duality enabled us to devise a custom research workflow based on a hybrid mode of investigation. We deliberately combined unrestricted, speculative artistic creation activities, geared towards exploring the fundamental esthetic aspects of design, with more rigorous research activities, taking the form of carefully designed architectural experiments involving computational design and robotic SPIF.

Our investigation started with the construction of a hypothetical design workflow and a set of digital techniques enabling its execution. The workflow and toolset were derived based on the results of our previous research involving the robotic SPIF process. Next, we validated this hypothetical workflow by carrying out a series of iterative design experiments that followed the steps of the workflow and that employed its accompanying digital toolset. Here, we devised three design cycles embracing intentionally-imprecise alterations of geometrical input and carrying out the SPIF process for each of these alterations. As these cycles proceeded, we were analyzing the suitability of the respective steps of the workflow and the enabling toolset for carrying out artistic explorations of geometric inaccuracies of SPIF. Having continuously refined our assumptions in the course of our experiments, we arrived at the final workflow and digital toolset suitable for implementation in esthetic exploration-oriented architectural design.

THE METHOD SUPPORTING ARTISTIC EXPLORATIONS IN ROBOTIC SPIF

Our proposal embraces a computational design method facilitating intentionally-imprecise explorations of esthetic variations of a design object's geometry materialized using robotic SPIF. The method gives access to the fine-tuning of polymer mold geometry from which architectural prototypes are cast. When formed incrementally, the mold undergoes unanticipated deformations due to internal strains induced by the forming process. Some areas sink down, while others are pushed upwards. These deformations result in local convexities and concavities that cause the physical outcome to differ locally from the silhouette of its digital original.

Moreover, the geometrical 'errors' of the mold cause the liquid silicone, cast into the mold, to accumulate in thicker layers around the convex regions and to become thinner in the concave ones. This varied silicone-settling culminates in color intensity and surface translucency increases and decreases, spread across the silicone cast. These optical effects comprise emergent aesthetic qualities added to the cast object, unanticipated and not designed from the beginning but interesting from the esthetic standpoint.

Our method also allows the designer to further explore these emergent esthetic qualities and through such explorations generate variations of the original design by tweaking the shapes, locations and sizes of silicone accumulation and thinning zones. In particular, the method gives access to the esthetic fine-tuning operations of extending, limiting, deepening and shallowing the mold deformations in chosen areas through semi-precise robot toolpath fine-tuning.

The digital toolset enabling such explorations combines parametric modeling, digital surface curvature analyses, digital photography, painted bitmap image creation and photogrammetry. The geometrical and numerical data produced with these tools are used as input for the exploration-oriented iterative computational design workflow, accessed through a custom-developed visual programming script. The script facilitates an iterative generation of mold geometry variations. Such variations affect the silicone settling patterns in the physical pieces.

The script allows the designer to demarcate the zones of the original digital surface that shall undergo fine-tuning. Further, it provides visual and numerical control of the scope and amount of applied geometrical change. Although employing computational means, in several points it is intended to accept input from less precise operations, such as freehand bitmap painting and arbitrary geometry depth adjustments. Additional moments of subjectivity and inaccuracy can also occur in setting the patch surface generation parameters, when determining mesh density, during the sampling of bitmap paint strokes onto the affected geometry points and when setting the parameters for mesh smoothing.

Our method is intended both for generating design objects that belong to pure art as well as for artistically developing the esthetic features of objects that are architectural, such as ornamental facade panels, decorative interior elements etc. The average dimensions of a bounding box of the elements produced in this study was H68 x W92 x D18 cm. The size of such molds produced using the industrial robot arm technology could probably be much larger and reach interior room or building façade dimensions. The maximum sizing will depend not only on the robot arm reach but also on a combination of other factors, important from the standpoint of the incremental forming process. Such factors include the individual geometrical deformations inherent for particular geometrical designs, strength and location of dynamic springback occurring during forming, forming angle, forming tool diameter, polymer sheet thickness, maximum material frame and backing plate sizing possible to manufacture and effectively support the material sheet etc. Extensive research is needed to further explore these scaling up aspects and determine the dimensional limits of polymer sheet SPIF.

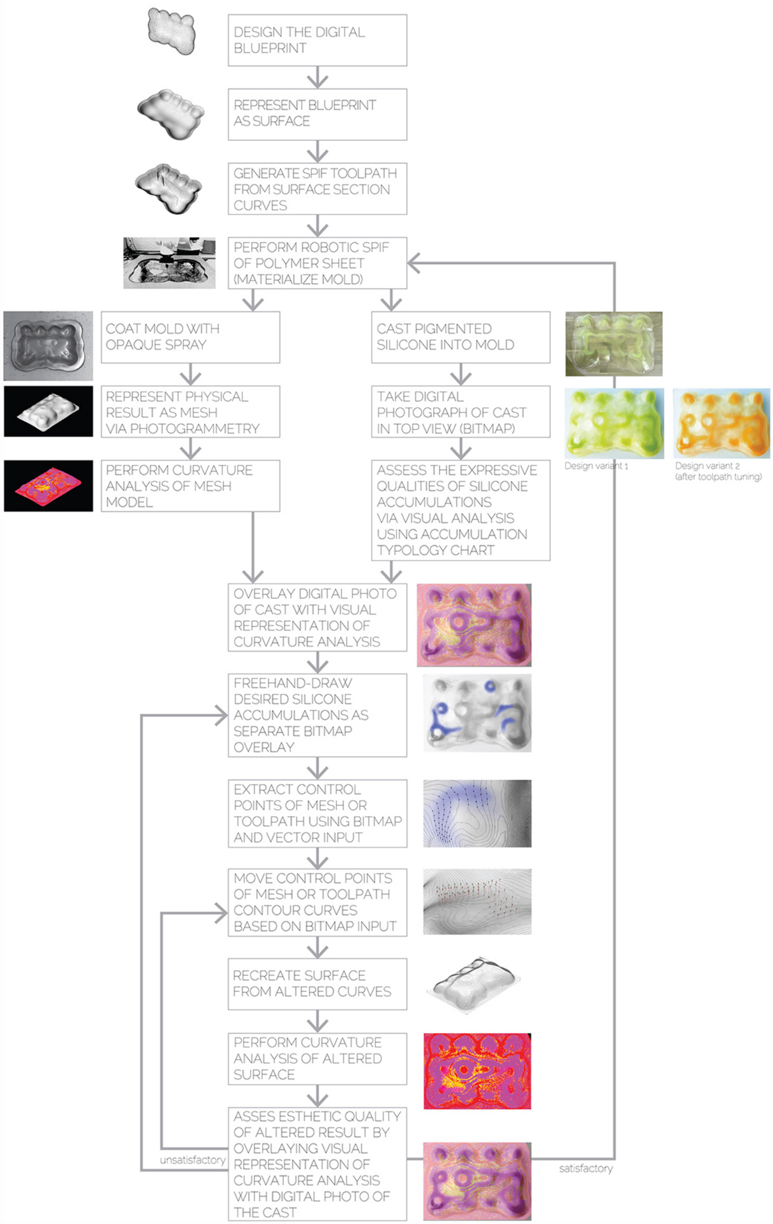
METHOD IMPLEMENTATION

To provide an understanding of our method implementation in the context of artistic explorations featuring imprecision, below we give an account of the first two design phases, encompassing design generation and the first geometry fine-tuning cycle. The steps of the design workflow accompanying such a fine-tuning cycle are also shown in Figure 1.

The explorations were carried out with the support of the two custom visual programming scripts facilitating the implementation of our method. The architectural purpose of the design objects produced in this study is related to the development of novel expressions for tangible interactive architectural interfaces, described in more detail in another publication (Zboinska, Dumitrescu & Landin, 2019).

Our exploration began with designing a digital object serving as a blueprint for the esthetic exploration process. By means of visual programming, we created a parametric metaball system outputting section curves that approximated the outline of our design object. The curves were then split in half along the longitudinal axis of the geometry to create

Figure 1
The iterative computational design workflow deliberately featuring imprecision to enable esthetic design explorations.



two assemblies, representing two mirrored sides of our object.

Next, one of the two symmetrical curve assemblies was used to generate a patch surface. To satisfy the needs of the SPIF process, that patch was rotated to a horizontal position and an outskirt surface was added at its border for improved formability. The patch and outskirt were then intersected with a set of cutting planes to obtain planar section curves. These curves underwent a series of parametric transformations, leading to the construction of a single polyline toolpath, legitimate for the robotic SPIF process. Finally, robot code for toolpath execution was generated and the first SPIF process was carried out using the code. Liquid pigmented silicone was then cast into the formed mold, yielding the first physical design instance.

Ocular comparisons between the digital blueprint, the physical mold and the silicone cast revealed the discrepancies between them. The major inaccuracies of interest for this study occurred at the originally convex areas of the digital blueprint. As shown in Figure 2, in the physical mold these areas became inverted, forming local concavities, which in the silicone cast presented themselves as local thinning and thickening of the cast material.

These unexpected local silicone accumulations caused by unplanned mold deformations inspired the workflow in the first cycle of digital geometry fine-tuning. We started by taking a top-view digital photo of the silicone cast. We also performed photogrammetry of the mold, to obtain its digital 3D mesh representation. With this step, we introduced the first moment of intentional inaccuracy, by choosing a less exact method of photogrammetry instead of ultra-precise 3D scanning for generating the digital representation of the mold. The aim was to generate a fine discrepancy between the physical result and its digital representation and to employ that intentionally less precise digital representation as input for design fine-tuning. The overall intention was to explore how this would affect the geometry of the next physical design iteration.

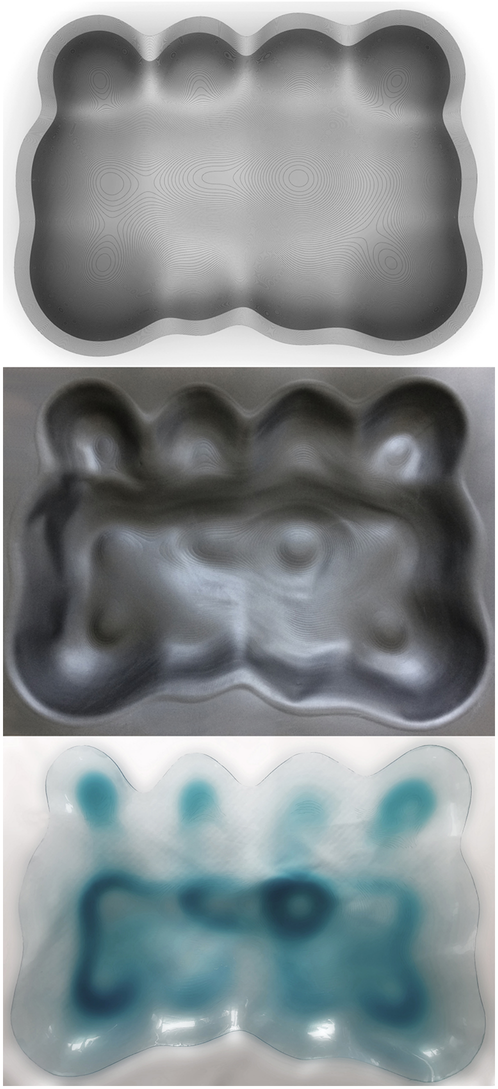


Figure 2
A comparison between the original digital input shape (top), the local geometrical deformations of the polymer mold (middle, coated for the purpose of photographing) and the resultant material accumulations in the silicone cast (bottom).

Having the mold represented in digital form, we then carried out a computational analysis of its mean curvature. The result was a false-color illustration visually reinforcing the locations of concave and convex zones in the mesh. Next, in a bitmap editing environment, we overlaid the images the silicone cast and the mesh curvature analysis. We then used them as guides for the process of less accurately and more casually painting the desired new silicone accumulation zones. These were painted instinctively by hand, using a series of digital brushstrokes, created in a separate drawing layer on top of the underlays. Upon the completion of this step, we saved a bitmap representation of the painted zones in an image file format. Additionally, we extracted the boundaries of the painted zones as curves in vector format.

The next phase encompassed importing the bitmap and the boundary curves representing the painted zones as inputs for our visual programming script. Using these two inputs, we then extracted and selected the vertices of the photogrammetry-derived 3D mesh to be affected by fine-tuning. The fine-tuning took place by moving the mesh vertices in the Z-direction by values generated based on color brightness sampling performed for the bitmap image representing the previously painted silicone accumulation zones. For a more arbitrary and imprecise effect, we introduced a multiplier for the movement values and an additional sine graph for remapping them.

In the final phase of the digital design cycle, we visually evaluated our final version of mesh point movement with the aid of a mesh curvature analysis for the altered mesh. Having assessed the result as esthetically-satisfying, we introduced another moment of inaccuracy, by subjecting the mesh to a process of smoothing after the move of the vertices, to achieve softer transitions between the fine-tuned and the unaffected mesh areas.

Our process continued towards completion with the contouring of the fine-tuned mesh in the 3D modeling environment. The planar curves resulting from the contouring became a basis for the construction of a new patch surface. That surface was used as an underlay for generating a robot toolpath and its execution program, using our second visual programming script. The program was then ran on the robot as the second SPIF process. Ultimately, silicone was cast into the robotically-formed mold, generating the first iteration of our design.

Having the physical result of this first iteration, we repeated the cycle of digital and computational fine-tuning, according to the workflow described above. For this second design iteration cycle, we also used the 3D representation of the second mold geometry generated via photogrammetry as input, to iteratively transform our design.

ESTHETIC IMPLICATIONS OF THE METHOD

Figure 3 illustrates the geometrical differences between the three molds produced using the intentionally-imprecise digital geometry and robot toolpath fine-tuning. Figure 4 shows the effects of the fine-tuning in the final design objects, appearing as varying silicone accumulations. Interestingly, accumulation shape typologies such as an island, an atoll and a lagoon emerged as a result of the fine-tuning. From the design conceptualization standpoint, such typologies can form a catalog of esthetic forms representing a formal vocabulary underpinning the fine-tuning of the first design. Such a catalog can become a point of departure for further playful explorations that either develop and reinforce the derived accumulation typologies, or strive to obtain new ones.

In addition, the esthetic result presents other features potentially original from the standpoint of architectural materiality. The first of those features encompasses the optical effects of seamless color and transparency transitions taking place within one material entity. These offer opportunities for further esthetic design development, such as explorations of transparent color overlays within a single architectural mass.

A second new feature relates to the tactile qualities of the resultant design object. The variations in material thickness and distribution cause variations in the stiffness and thickness of the silicone cast. The object mass seamlessly morphs from thin to thick and from soft to stiff across the object surface, with no sharp property changes in-between. Additionally, as shown in Figure 5, the line-work following the path of the tool from the forming process is captured within the cast, forming an inherent detail with an unusual optical effect and tactile potential.

These features bring in esthetic qualities that can mediate a novel visuo-tacile experience of architectural materiality, achieved through an unconventional treatment of architectural material as a voluminous substance designed to convey bulk, thickness and texture. Moreover, the scalability potential of the robotic forming process suggests that objects such as the ones presented in our study could easily become walls, floors and ceilings, cast as single, monocoque pieces that enrich the experience of architectural space through their exotic materiality.

REFLECTIONS ON METHOD APPLICATION

The key strength of our method is that it enables creators to explore design iterations in a hybrid mode, combining more spontaneous artistic activities with operations based on computational logic. It provides high levels of expressive freedom at the intentionally-imprecise moments of the design process, while also exploiting the capacities of computation to facilitate materialization of geometrically-complex designs. It also offers the possibility to benefit from the imprecision of the fabricated object by using it as a catalyst for esthetic explorations.

One of the main challenges of using our method is that it demands a deep understanding of the material behaviors accompanying the incremental forming process. It also requires fundamental knowledge on other types of forming inaccuracies that affect the geometrical deformations studied herein, accompanied by a thorough comprehension of the relationships between the material behaviors, the particular shape of the formed geometry and the process requirements.

The application of our method also involves a risk of failure upon each iteration run due to the high unpredictability of the dynamic springback occurring upon forming that may cause material breakage.

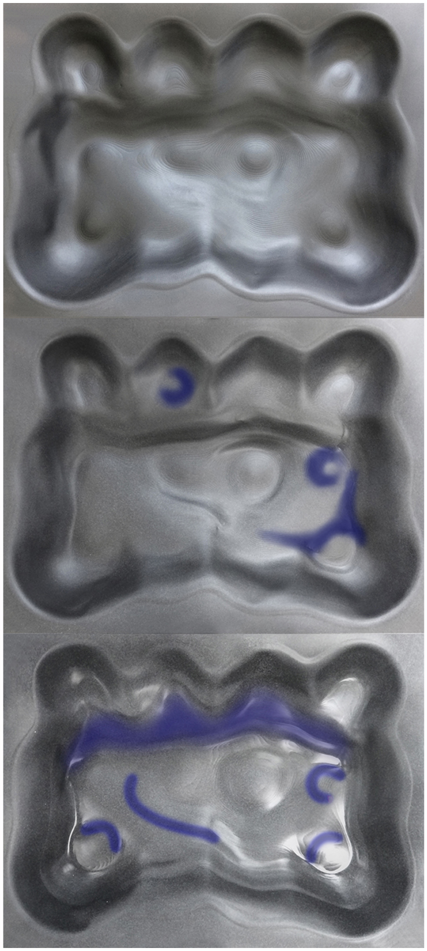


Figure 3
A comparison between three polymer mold geometries created with the aid our method (coated for the purpose of photographing and accurate illustration of geometrical differences). The top mold is the first design while the middle and bottom molds are its iterations. The location of digital paint strokes used as a basis for the intentionally-imprecise computational toolpath fine-tuning is indicated in blue.

The effect is highly dependent on input geometry size, shape, local curvatures and the nature of their transitions. As our experience with the process reveals, even a small alteration in the shape and curvature of the input geometry may cause the process to fail. Therefore, some designs may be possible to fabricate, while others may not. Without additional digital simulation aids it is difficult to predict which will be the case without carrying out the forming process.

Figure 4
Three design iterations, featuring differing silicone accumulations, obtained owing to the application of our method in the exploration process.

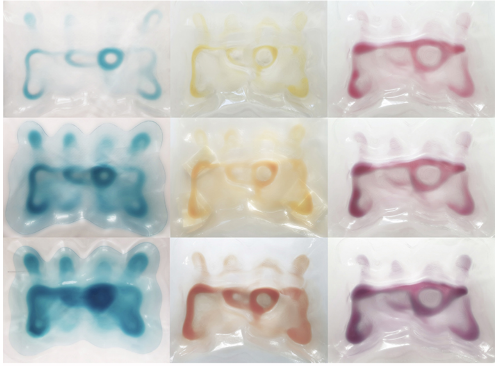


Figure 5
Original esthetic qualities, embracing inherent textural properties, unusual transparent color transitions and unconventional volume treatment featuring varying thickness and stiffness of the architectural material within one mass, all arising from the application of our method in the design process.

To implement our method in the creative industry and the building sector, extensive further research is hence needed that aims to develop architect-friendly computational simulations of dynamic material behaviors occurring during forming and indicate which geometries are feasible for successful SPIF processes. Such interdisciplinary research needs to take place at the intersection of architecture, manufacturing and material engineering.

CONCLUDING REMARKS

With the results of this study, we contributed to the broadening of the existing knowledge on the forming of polymers for architectural purposes. We analyzed how the geometric imperfections inherent to the forming of this material can be generative in shaping the esthetic expression of the formed object. Inspired by the need to explore unfamiliar architectural applications of SPIF, we also provided an example of a novel utilization of SPIF to produce molds for casting single non-panelized architectural pieces from a liquid material.

Our study yielded a method of digital design that transforms the fabrication inaccuracies from unwanted annoyances to desired, intrinsic features of the design that can be explored as esthetic variations. We promoted working intuitively and in a deliberately imprecise manner within a computational environment, while also ensuring that the design results from our process are relevant and novel from the esthetic standpoint. Our account of the method implementation demonstrated how the designer can shift focus from ultimate control of material behavior and geometric accuracy towards unrestrained digital explorations of the novel esthetics of imprecision. Through this, we have shown that it is possible to transform the limitations of tools and materials into virtues, providing opportunities to innovate at the artistic level of design.

Our method allows for the viewing of computational design from a refreshing perspective, marked by curiosity-driven explorations of computational processes and their influence on unpredictable material behaviors. We hope it will play a role in promoting further advances in the research, education and practice of creative architectural robotics. The provision of such new methods is intended to inspire the development of other approaches to handling inaccuracy for esthetic design purposes in architecture. Such approaches will be crucial for rejuvenating interest in artistic, liberal and spontaneous ways of creation within architectural computation.

Ultimately, we hope to have demonstrated that in the age of the fourth industrial revolution, which we believe is a revolution of digital creativity, the application of digital technologies does not need to fixate on the production of accurate designs only. Positioning imprecision as a design prerequisite that is as valid as accuracy opens a vast, excitingly unknown territory of design explorations that can interestingly alter the image and perception of contemporary architecture. Architectural objects can authentically reflect the nature of the imperfect processes behind their becoming. This fact lays the foundations for the emergence of new paradigms in expressing the materiality of tomorrow's digital architecture.

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