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Variable Pneumatic Thermoforming

Robotic Thermal Welding for Volumetric Thermoplastic Building Envelope Panels

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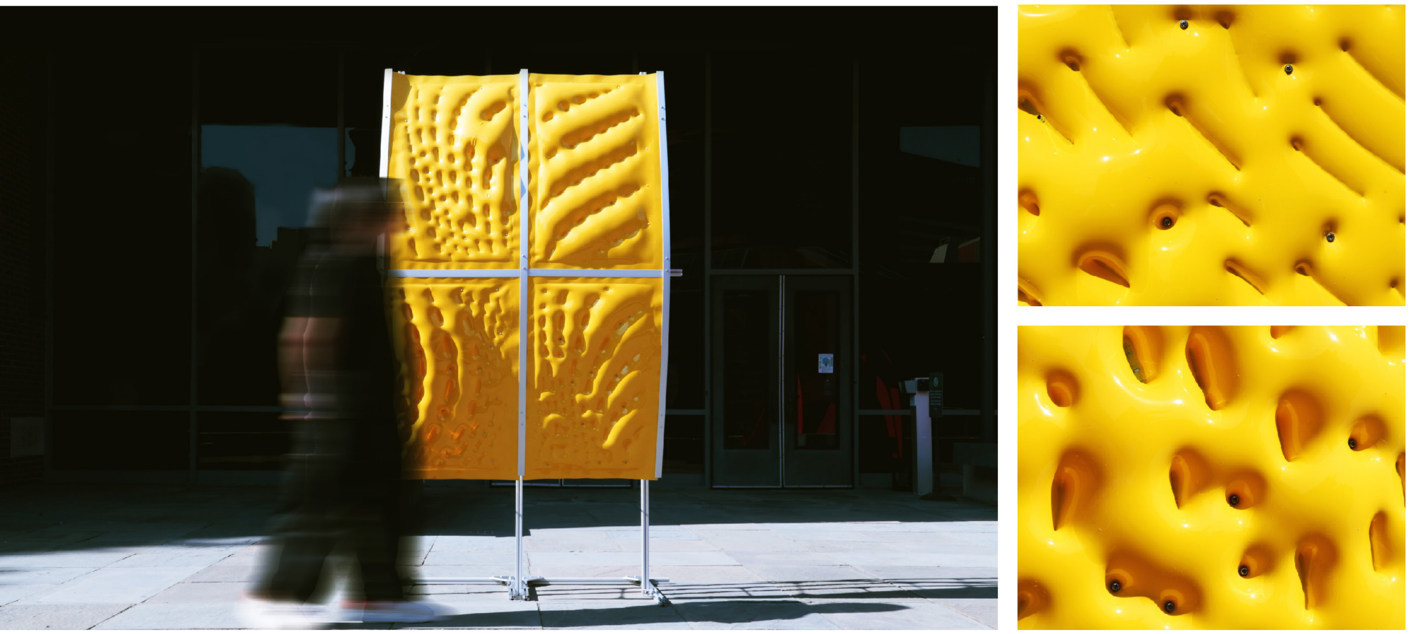

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1 Prototype for Variable Pneumatic Thermoforming. Aesthetics resulting from pneumatically thermoformed PETG panels.

ABSTRACT

Thermoplastic sheets are extensively used for the manufacturing of everyday-use products, such as packaging, automotive parts, and construction components, due to their rapid formability and recyclability. Thermoplastic sheets are produced at high volumes and can be manufactured into volumetric forms by thermoforming, hydroforming, and pressure-forming processes. Despite their benefits, these industrial techniques require a mold or form that renders shape variation challenging and costly within a single production run. This constraint poses a critical question: How can one bypass traditional mold-based thermoforming methods to produce bespoke parts using sheet materials? In response to this question, this research explores the integration of robotic thermal welding techniques to guide a variable pneumatic thermoforming process. This research tests this method to unlock the potential for custom, repeatable, and controlled bespoke fabrication using thermoplastic sheets. The process utilizes a custom end-effector and a 6-axis robotic manipulator to selectively laminate two PETG sheets using thermal welding. First, a perimeter with a specific boundary profile is welded that contains the inflation forming. Within that boundary, points, lines, and curves are distributed to create unique thermal welding patterns that constrain inflation to generate varied volumetric formal outcomes within a laminated panel. Post-lamination, the sheets are heated to their glass transition temperature, and a controlled staging of compressed air is introduced inside the panel. This forming technique produces semi-rigid volumetric components with an inner cavity and a consistent boundary condition. Following a series of prototypes that proved the efficacy of the manufacturing process, a simulation model was developed and utilized to inform the

INTRODUCTION

The Architecture, Engineering, and Construction (AEC) industry relies on the mass production of standardized parts with a consistent supply chain. This approach has many benefits, including lower-cost production, but often limits formal freedom in design. Molding and forming methods, such as casting, injection molding, and thermoforming, depend on expensive and inflexible molds (Athanasiou 2009). For variation, each unique component requires a new mold, form, or tool, thus increasing costs and adding complexity to the manufacturing process. This reliance on standardization reinforces the industry's preference for repetitive designs.

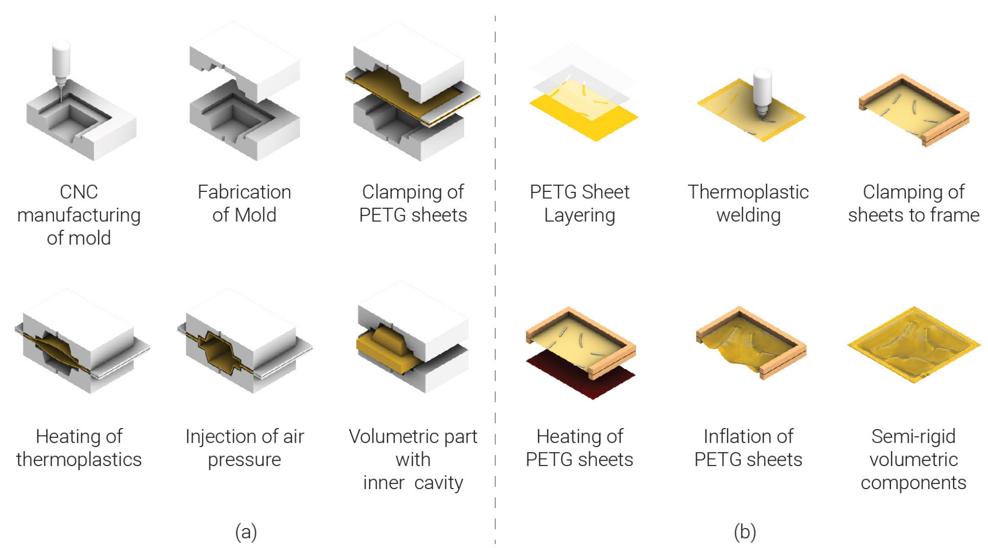
Both thermoset and thermoplastic products are used for building applications such as building envelopes, roofing, furniture, and interior fittings, including corrugated panels and roofing sheets (Knippers 2011). In the case of thermoplastics, these components start as thermoplastic pellets and are initially melted and extruded through dies to achieve a form, including sheets. Different secondary manufacturing techniques are sandwiching, where plastic sheets are layered with channels; thermoforming-vacuum molding, where plastic sheets are formed using a one-sided die and vacuum forming, where sheets are locally heated and shaped with enhancing stiffness (Knippers 2011). While effective in strengthening, these methods typically produce uniform, repetitive shapes restricting the potential for varied geometric designs

Addressing these limitations for building envelopes requires innovative approaches to mold-making and fabrication processes, which would enable architects to explore more diverse forms without prohibitive costs. This poses the critical question: How can we develop a thermoforming technique that bypasses traditional mold and cost fabrication limitations to produce bespoke building envelope parts?

This research leverages the material forces inherent in thermoplastics to create variable aesthetics, proposing a paradigm shift in architectural fabrication. Our research contends that the use of robotic fabrication coupled with digital simulation can enable the production of bespoke parts with complex volumetric geometries. This approach challenges traditional, repetitive thermoforming methods by introducing a variable method that generates differential surfaces. By leveraging the flexibility and adaptability of thermoplastics, the research aims to demonstrate that advanced fabrication technologies can produce highly customized, aesthetically diverse components, thus overcoming the limitations of standardization and fostering greater creative freedom in architectural design (Figure 2).

STATE-OF-THE-ART

In terms of shape-making, this research is situated within a field of generative fabrication studies that have explored variable molds in architecture for dynamic design fabrication using materials like concrete (Kudless 2009)(West 2008), glass (McGee et al. 2012), textiles (Yan Ng and Ahlquist 2020), and metals (Ayres et al. 2011)(Zieta 2008). Andrew Kuddless and Mark West have utilized adaptable membrane materials as formwork for cast concrete to diversify concrete facade designs, where points and seams in the fabric dictate the concrete forms (Kudless 2009) (West 2008). Tsz Yan Ng and Sean Ahlquist have developed a CNC manufacturing method for creating knitted, volumetric formworks (Yan Ng and Ahlquist 2020). McGee et al.have used pin-molds to craft double-curved glass structures



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2 (a) Typical pressure-forming process, a common mold thermoforming fabrication, compared to (b) Variable Pneumatic Thermoforming fabrication process

(McGee et al. 2012). Ayres et al. and Zieta have experimented with welding metal sheets that, once inflated, form rigid components with internal cavities (Ayres et al. 2011) (Zieta 2008).

Our research explores the potential of moldless forming processes for thermoplastic sheets — specifically PETG. This material provides several advantages, such as UV resistance, high durability, and easy recyclability. Compared to glass, it is lighter in weight, thus requiring less structural support. PETG is a thermoplastic with a relatively low melting temperature, so its suitability for building envelope applications may be limited. However, this research focuses on the forming process that can be generalized to other thermoplastics.

Research in thermoplastic forming has primarily focused on two areas: non-rigid, extensible polymers and single-sheet forming that involves human-robotic interaction. Research in air-assisted forming focusing on form exploration often involves stretchable non-rigid materials such as textiles (Ahlquist et al. 2017)(Baranovskaya et al. 2016), silicone, PET film (Lin et al. 2022), latex (Poinet et al. 2016), vinyl (Schumann et al. 2021), LDPE film (Velikov et al. 2014). These studies focus on how materials can adapt and shape during inflation, allowing for varied forms. Given their dynamic and non-rigid nature, these studies rely on a constant inflation system to maintain the form.

Welding technologies for sheet materials have been coupled with robotic fabrication to augment their application. Different types of welding technologies offer different efficient and robust joining results (Costa et al. 2012). Li et al. examine the application of ultrasonic welding in fiber-reinforced thermoplastic composites, highlighting its advantages (Li et al. 2022). Additionally, Gohlke et al. propose an approach named 'WireShape,' which utilizes CNC-fabricated heat-sealing tools for rapid and reliable manufacturing of inflatable structures, demonstrating the potential of advanced fabrication techniques in enhancing the production of thermoplastic-based structures (Gohlke et al. 2023). Then Baicun et al. explore the integration of artificial intelligence into robotic welding systems, delineating how these advancements are transforming traditional welding practices into intelligent welding systems (Wang et al. 2020). These studies underscore the importance of welding technologies in enabling innovative applications for further research on variable pneumatic thermoforming design.

Typically, manufacturing rigid objects from thermoplastic sheets research involves the manipulation of only single-sheet thermoplastics. These processes in research implement a human-robot interaction process (Mueller et al. 2019)(Schumann et al. 2019) or a reusable formwork (Swackhamer et al. 2013). Whereas their research establishes a precedent for pneumatic thermoforming, our research uses two sheets of thermoplastics, creating an inner cavity, presenting a potential for insulative properties.

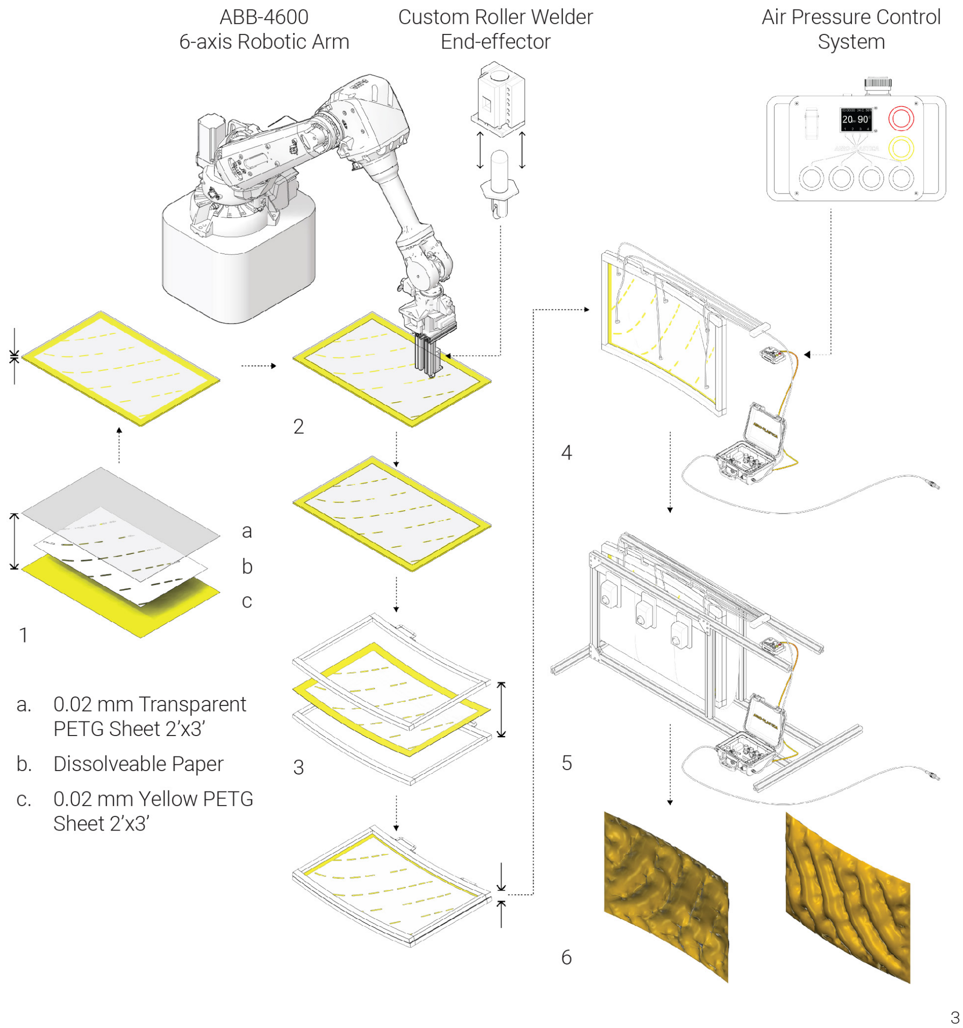
Variable Pneumatic Thermoforming combines thermoforming techniques with pneumatic forming used by Ayres et al. and Zieta to develop an integrated approach to pneumatic thermoforming. This process results in semi-rigid volumetric panels with increased depth, offering opportunities to potentially provide the greater insulative and spanning capability. This outcome has potential applications in building envelopes where increases in volume and rigidity are often leveraged for insulative and self-structuring envelope benefits. This research presents a feasible alternative to current plastic thermoforming practices and future opportunities for the digital fabrication of plastic building envelopes.

METHODS

The workflow of the Variable Pneumatic Thermoforming method includes design, and iteration of the design based on a digital simulation, PETG sheets and frame setup, thermal welding of sheets with a robotic end-of-arm tool (EOAT), heating of sheets, and inflation of the laminated sheets, followed by their cooling to become semi-rigid panels (Figure 3). To achieve variability and control of each step, a fabrication and design approach was developed that included: material definition, a thermal welding tool EOAT, edge control, heating setup, air insert, digital simulation, and welding pattern testing. Each of these was engaged in a series of experiments that evaluated viable parameters for supporting successfully controlled inflation for variable formal outcomes and their suitability for both design and manufacturing activities. Following these experiments, the approach was applied to the design, fabrication, and assembly of a multi-panel prototype that explores the formal possibilities of the fabrication method for a building envelope. While the research does not engage in the detailing or performance criteria of a building envelope, working at this scale enables an evaluation of the formation approach for such applications.

Material Definition

The constraints in our fabrication laboratory with recycling and logistics informed a decision to work with PETG. We evaluated our process's aesthetic outcomes and scalability using transparent PETG sheets with thicknesses of 0.02",



3 Variable Pneumatic Thermoforming workflow process. (1) PETG sheets layered together. (2) Robotic thermal welding. (3) Welded PETG is placed between two curved frames. (4) Set up an Inflation apparatus, placed vertically. (5) Heating on a heat bed. (6) Semi-rigid volumetric panel

0.03", and 0.04", and yellow PETG sheets at 0.02" thick. Sheet sizes tested included 12x12", 12x24", 12x48", and a larger prototype panel of 24x36".

Bonding Control – The ability to control the selective lamination of the two sheets

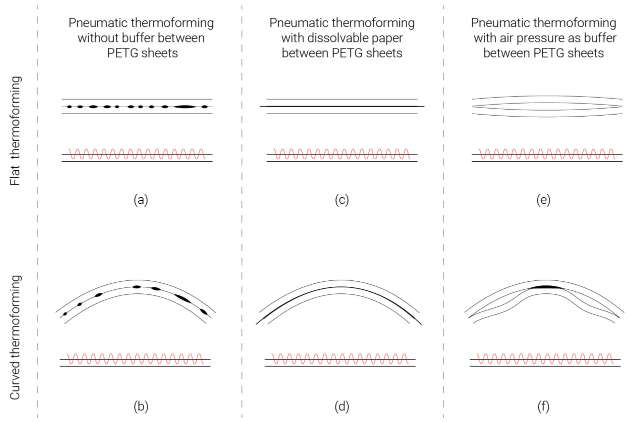
Accidental bonding between sheets during the preheating stage is a challenge in the pneumatic thermoforming process of PETG sheets. This study evaluates two methodologies to mitigate this issue (Figure 4). (1) A physical buffer, such as a dissolvable paper, is inserted prior to the welding process between sheets to ensure no accidental bonding. This method requires cutting the paper to maintain the welding integrity. (2) An air buffer intended to replace the physical barrier. Low-pressure air is introduced between the layers during the preheating phase. This method is advantageous for its simplicity but only efficient in designs with less intricate welding patterns.

Thermal Welding Tool – The end of arm tooling (EOAT) needed to locally weld two sheets.

Plastic welding technology is vital in pneumatic plastic sheet molding. Among the various plastic welding methods, we identify thermal and ultrasonic welding, which are easier to access and operate (Costa et al., 2012). We used several tools, including a soldering iron with different tips, a roll welder, and an ultrasonic welder to achieve a durable and tight seam.

Edge constraints – To control global form, a frame is needed during the process.

This research explores the challenge of controlling the global form of each component during the formation process. Inflating the sheets without a frame resulted in uncontrolled edges of the inflated parts; this caused difficulty in predicting and control the shape of the final product, essential for multi-part assemblies. A rectangular wood frame was built and equipped with clamps to hold the two sheets in a fixed position during inflation. This allowed for precise control over the edges of the sheets as they were formed (Figure 5).



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(a) (b) (c)

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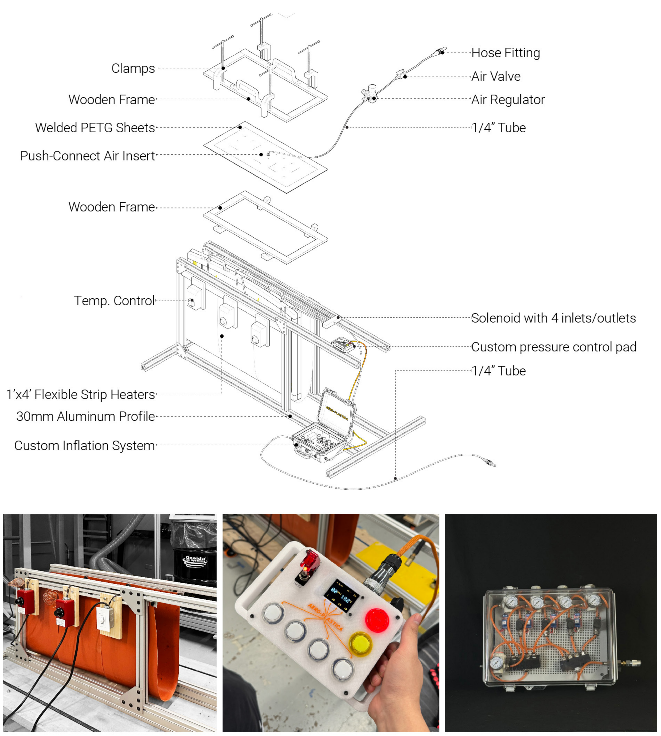

(a) (b) (c)

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Custom Heating Rig – The pneumatic thermoforming requires global heating (in addition to previously undertaken local thermal welding)

To reach the PETG sheets' glass transition temperature of 85°C, we initially used one 12"x48" silicone rubber flexible strip heater, capable of reaching up to 450°F (~232°C). This enabled the use of 12"x48" PETG sheets for single-sided heating or 12"x24" sheets for double-sided heating (where the strip heater was folded over to cover both sides of the PETG sheet). Double-sided heating ensures that both sides of the sheets receive simultaneous and uniform heat exposure. The ability to evenly heat both sides of the sheets significantly enhanced the quality and consistency of the inflation process. To optimize and allow the heating of larger sheets, a custom-built heating rig was designed using 30mm t-slotted aluminum profiles to hold three flexible strip heaters, extending the heated area size to 24"x36". This arrangement allowed for double-sided heating with the frame holding sheets in between. This fixture was suitable for prototyping and would be further developed for a larger production volume (Figure 6).

Inflation point – Defines the location for the selective introduction of compressed air

Effective air injection into the thermoplastic cavity is critical in the process for reliable inflation and repeatability control during pneumatic thermoplastic sheet forming. Two methods of air inlets were used during our experiments: (1) A flat copper tube inserted between the two PETG sheets. (2) A threaded push-to-connect fitting screwed on one of the two PETG sheets (Figure 7). The former method proved difficult to seal, resulting in significant air leakage during inflation and unpredictable expansion. The latter technique involves drilling the hole and flow control orifice, which provides a more controlled and reliable inflation by ensuring a tighter seal.

4 Strategies to prevent accidental bonding during the heating process in pneumatic thermoforming for flat and curved forms: (a)(b) No strategies applied (c)(d) Utilization of a dissolvable interlayer to separate material sheets, ensuring selective adhesion, (e)(f) Implementation of low-pressure air injection to maintain separation between layers, suitable for simpler patterns. The air-buffer proved successful only in flat surfaces. The dissolving paper proved successful for all cases but requires an extra step.

5 The results of the global form depend on the edge condition. (a) Thermoforming with wooden frame. (b) Thermoforming without any frame. (c) Thermoforming with a wooden frame to minimal edge control. The use of a frame enables a controlled boundary and inflation for each component.

6 (Top) Exploded axonometric detailing components for the heating and inflation of thermoplastic sheets. (a) Image of the custom heating rig. (b) Close-up for the custom control panel for pressure control. (c) Custom solenoid and valve system for pressure controls.

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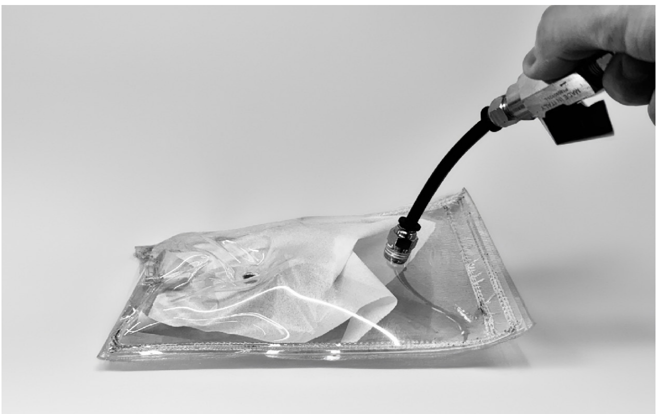

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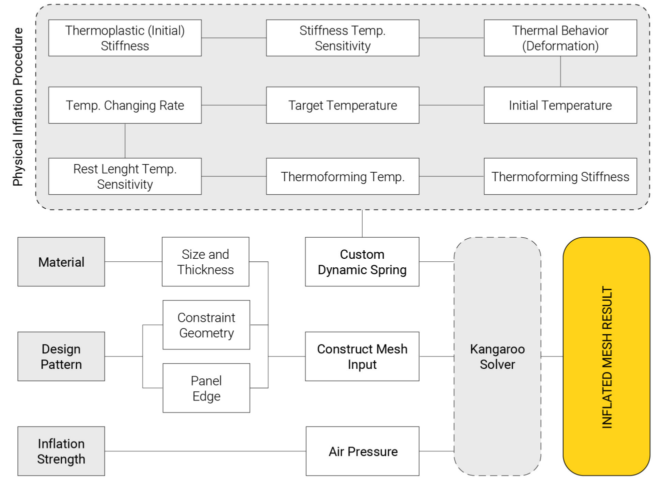

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7 Push-connect fitting for inflation point. This system allows for a sealed connection between the air input and thermoplastic sheets preventing air-leakage during inflation stages.

8 Demonstration of material stiffness being enhanced by increases in panel depth and stiffness from the Variable Pneumatic Thermoforming processs. Material before pneumatic thermoforming is compared to the enhanced stiffness after pneumatic thermoforming.

9 Digital simulation input and variable parameters for material reaction, seaming patterns, and algorithmic logic to inflate plastic sheets in Rhino Grasshopper to predict inflated forms.

Pattern – Form is generated based on the location of selectively welded points, lines, and curves.

Adding thermally seamed patterns to PETG sheets serves a dual purpose: it enhances the panels' aesthetic appeal and significantly increases their stiffness. The strategic placement of thermal weld of dots, lines, and curves creates varying depths after inflation. This controlled expansion not only shapes the panel but also adds structural stiffness to the final form (Figure 8).

Digital Simulation

In order to predict inflation forms without creating physical prototypes, we developed a computer simulation model operating in Rhino3D 7 and Grasshopper (Figure 9).

The workflow begins by constructing a mesh with defined boundaries and patterns. The mesh vertex layout is then adjusted according to the pattern. Vertices at the pattern and boundary are fixed to represent the welded seam and boundary, respectively. Following this setup, the simulation conducts soft body simulations influenced by air pressure and temperature changes on the sheets using the Kangaroo2 plugin (Piker 2013) and a custom "DynamicSpring" class written in C#. This class, based on mass-spring systems (Mesit 2010), dynamically alters spring properties with temperature (Figure 10). We defined internal spring force equation as follows:

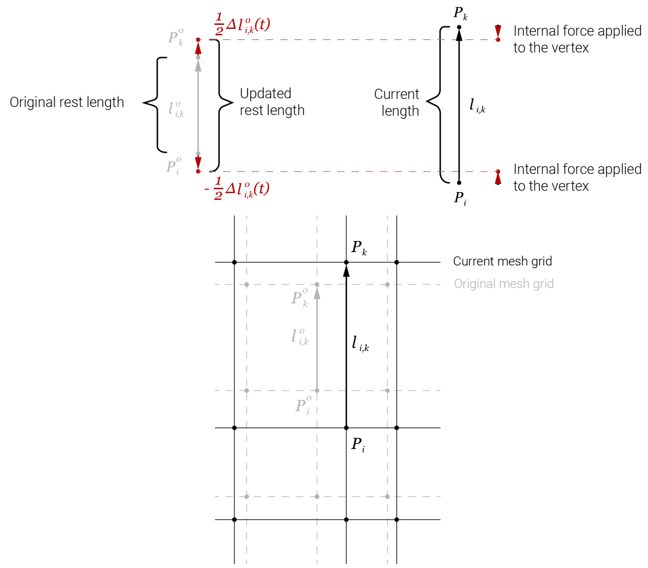
$$F_{int}(i) = -12kadj(t)kN(i)(li, k0 + li,k(t) - li, k)li, kli, k \quad (1)$$

Where:

- Piis the point for calculating internal forces.
- N(i) is a set of neighboring points connected to Pi.
- Pk is one of the neighboring points connected to Pi.
- li, k is the vector from Pi to Pk, indicating the direction and magnitude of the force exerted by the spring.
- li, ks the current length of the spring between Pi and Pk
- li, k0represents the original rest length of the spring.
- li,k(t) is the change in rest length due to temperature, calculated as:

$$li,k(t) = (li,k - li, k0) \times rl(t) \quad (2)$$

- Here, rl(t) is the rate of the rest length change related to the temperature at time t, adapting how the rest length responds as the simulated material becomes stiffer when cooling (Figure 9). The temperature-dependent behavior of the rest length (Clavet et al. 2005) in our "DynamicSpring" model, as detailed in equation



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10 Part of the mesh grid representing the PETG sheet before and after deformation (top). Scheme for calculating internal forces (bottom).

(2), aligns with the viscoelastic properties commonly observed in polymers such as PETG when undergoing deformation (Schaller 2022).

- The stiffness of the spring, kadj(t), dynamically adjusts with temperature changes according to the thermo-mechanical properties of PETG.

Our custom simulation with the "DynamicSpring" class adheres more closely to physical laws than Kangaroo's standard soft body component, accounting for heating and cooling processes. Theoretically, this method can enhance the accuracy of predictions, useful for precise developments.

Prototype

To demonstrate the feasibility of proposed thermoplastic sheet forming method, a large-scale prototype was developed consisting of four 24"x36" panels. Each panel is composed of two layers: one transparent 0.03" thick and one yellow 0.02" thick PETG sheet. The panels were welded using a heated roller attached as the end-effector on an ABB 4600 6-axis robot. During the heating and inflation stages, the sheets were secured and constrained with a curved wood frame. The completed prototype measures 4'x6'. The patterning of each panel is dynamically controlled by seams and point constraints aligned to create continuous lines. The pattern then can be extended beyond a single panel, creating a cohesive assembly.

RESULTS & DISCUSSION

Challenges of increasing PETG sheet size

To evaluate scalability of the Variable Pneumatic Thermoforming method, a series of tests with different sheet sizes were executed (Table 1). Initial tests were performed using 12"x12" PETG sheets of 0.02" thickness. Later, we scaled up to 12"x24", 12"x48", and ultimately 24"x36" PETG sheets of 0.05" thickness.

Increasing in size presented issues like uneven inflation depths and the bursting of the sheets. This was caused by the air insert location, patterns, and uneven heating. To address this, the heating rig was modified to accommodate larger sizes and double-sided heating, the number of air inlets was increased to provide even inflation throughout the panel, and an electronic air pressure control system was developed.

Bonding tests

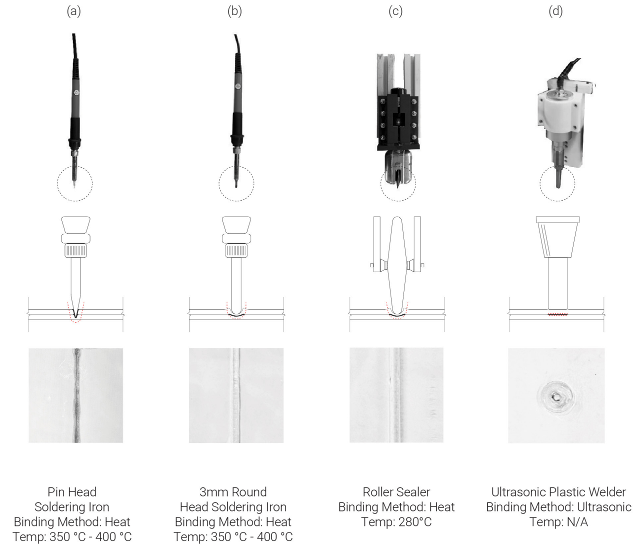
Both physical and air buffers were effective in avoiding accidental bonding of sheets. The physical buffer requires accurate cutting which increases the material and time of the process. The air-assisted buffer, however, is limited to flat inflations as the bonding is creating when the sheets are in contact with each other during the preheating phase.

Table 1. Recorded data for selected tests increasing in plastic sheet size.

NO.	SHEET SIZE (in.)	HEAT RIG TEAMP.(C°)	TOP SHEET TEMP. (C°)	SIDE HEATED	FRAME	AIR PRESSURE (PSI)	INLETS	ADD PAPER	BURST
1	12X12	160	80	1	YES	20	1	NO	NO
2	12X12	180	85	2	YES	25	1	YES	YES
3	12X12	180	90	2	NO	25	1	NO	NO
4	12X24	170	90	1	YES	1 TO 20	2	YES	NO
5	12X24	170	90	2	YES	1 TO 20	2	YES	NO
6	12X36	170	100	1	YES	20	4	YES	YES
7	24X36	170	90	2	YES	1 TO 25	5	YES	NO
8	24X36	170	100	2	YES	1 TO 25	6	YES	NO

Welding tests

Initial tests utilized a pinhead soldering iron with a temperature range of 350-400°F. This method faced challenges with seam stability. The manual application with the soldering iron led to a lack of precision, as it dragged material in this path. This caused the seam to be uneven with varying depths, compromising the tightness of the seal and aesthetic of the panel. To improve the quality, a roller tool was implemented, which minimized friction and maximized contact surface, significantly enhancing the seam quality (Figure 11).



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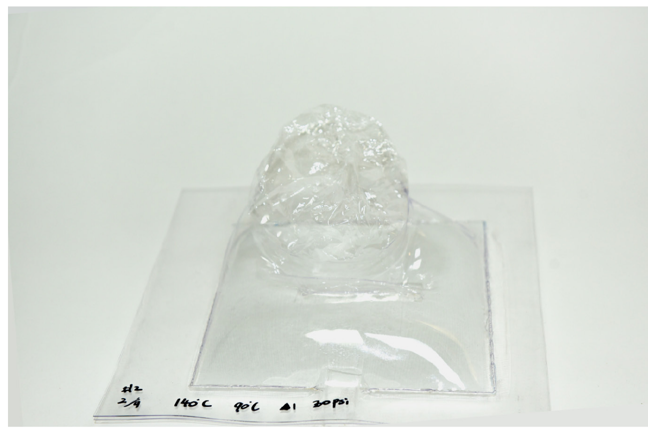

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11 Effects of different seaming/welding tools on PETG sheets. (a) Pinhead and (b) 3mm Round Head soldering tools require a minimum surface area for welding. (c) Roller Welder and (d) Ultrasonic Welder require the greatest amount of surface area. A larger welding area allows for a stronger seal but compromises the aesthetic results.

12 Failed result of sheet burst caused by one-time air opening.

The challenges of manual control led to the adoption of an ABB 6-axis articulated robot equipped with the roller welding tool. This robotic system's tool paths were prepared in Rhino3DGrasshopper's Visose Robots plugin (Soler 2015), enabling the simulation of robot inverse kinematics and the exportation of an ABB Rapid program that enabled precise control over the welding path, ensuring uniform depth and quality of the seal.

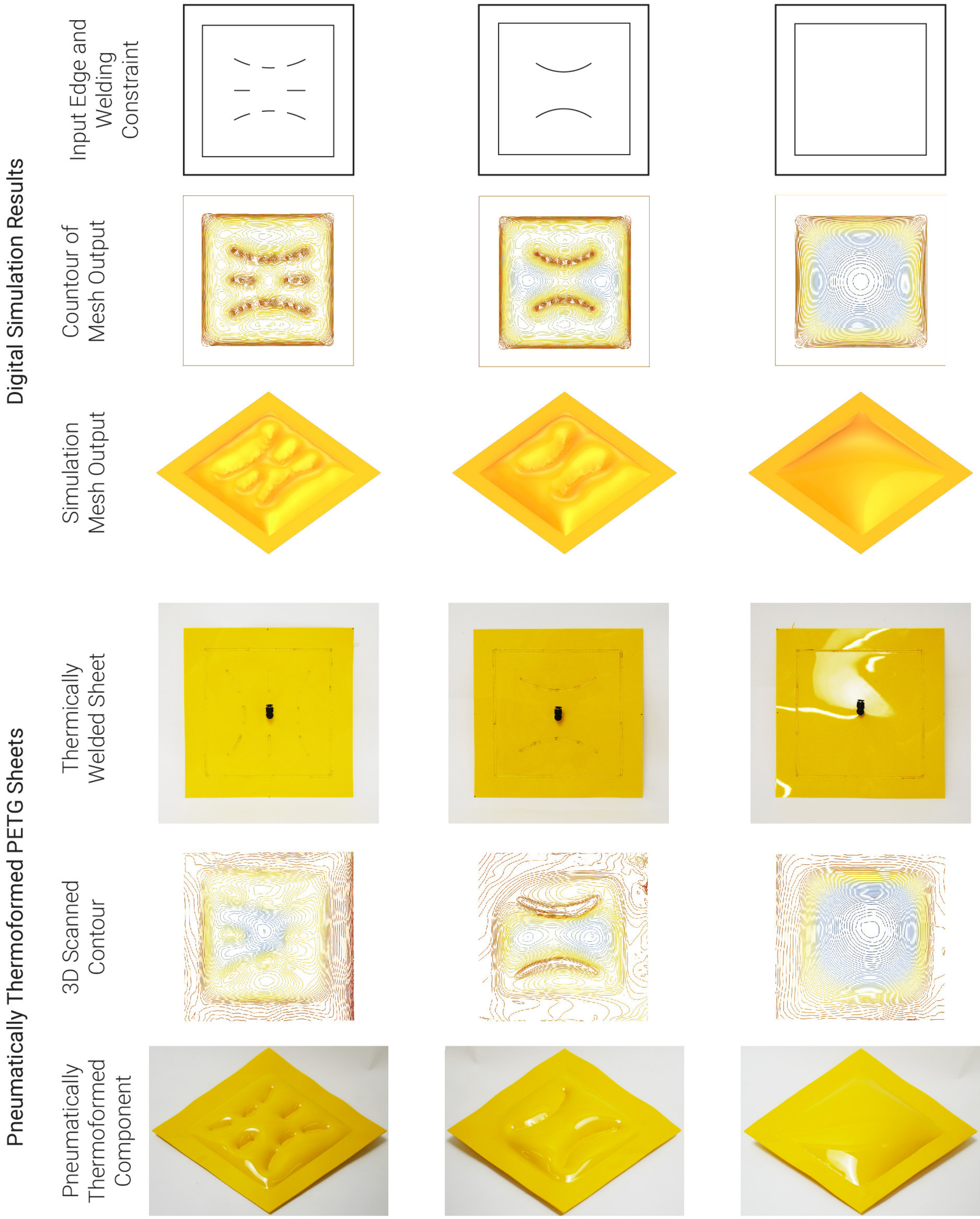
Roller welding proves to be successful for welding longer lines or curves, providing strong and durable seals. However, challenges arose when welding shorter lines or dots, as the seals tended to break during the inflation process due to insufficient bonding between the two surfaces of the sheets. Physical bonding methods, such as bolts and nuts to securely join plastic parts, were explored to address this issue. These methods offer a viable alternative to traditional welding techniques, ensuring more reliable seals in areas where heat welding was less effective.

Air Pressure Control

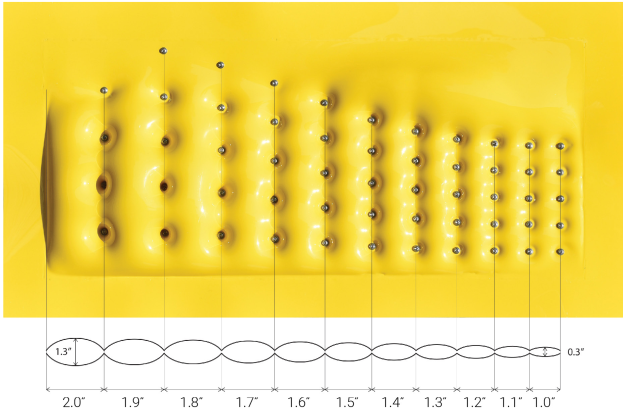
To control the air pressure at the inlet, an air regulator was attached to the air line. An abrupt opening of the valve often led to an overstretching of the thermoplastic, resulting in a burst (Figure 12). A gradual opening of the valve allowed for more control over the inflation process, ensuring the integrity and desired shape of the output geometry. To achieve repeated control of the air input, we developed a pneumatic control system programming an Arduino board to control 4 solenoids and 4 regulators. The solenoids and regulators were correlated to pressures of 1 psi, 5 psi, 10 psi, and 20 psi, respectively. When a button is pressed, the corresponding solenoid is turned on and air pressure is released, resulting in a gradual inflation. This control system provides a more regulated and repeatable inflation process.

Digital Twin Simulation

The material physics simulation model developed serves as an effective tool for approximating designs. It produced a mesh where each vertex is equipped with a dynamically changing spring responsive to input parameters based on PETG material and physical properties. However, it failed to simulate all environmental aspects during the inflation, as it assumed even heating and air distribution between the sheets. Yet, the simulation is highly valuable for overarching design objectives, particularly in the contexts of pattern optimization and architectural scale design. These observations have resulted in an interplay between physical setup adjustments and simulation parameter tuning, highlighting the balance required to achieve accurate predictive modeling in architectural designs (Figure 13).



13 Comparison of the prediction of pnaumatically thermoformed simulation (top) with the physical prototype (bottom) through three-dimensional contour of the simulated meshes with the contour of the 3D scanned mesh from the prototype. The simulation shows close prediction of the prototype form, however, it presents inaccuracies as it disregards external parameters, such as environment temperature, humidity, even heating, etc.



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14 Relationship between the distance among point constraints and magnitude of inflation after thermoforming process.

15 Custom simulation model outcomes illustrating the influence of pattern scale on pneumatic inflation magnitude.

Pattern Tests

The inflation of PETG sheets is influenced by the ratio of unconstrained surface area and constrained welded seam pattern inside of the sealed perimeter. Two different types of patterns were tested: (1) a gradient pattern to to understand the influence of the distance between constraints and the inflation volume; and (2) a reaction-diffusion pattern to evaluate the capacity for variable forming of complex forms.

Gradient Inflation Pattern Test

In the initial phase of our experimentation, a gradient inflation pattern was tested to evaluate the influence of pattern size on the pneumatic thermoforming process (Figure 14). We devised a pattern comprising dot constraints of with gradual distance increments, starting from 1 inch (~ 2.5 cm) to 2 inches (~5 cm). The magnitude of material displacement during inflation varied proportionally with the size of the constraining pattern. This phase was crucial in determining the optimal pattern sizes that avoided underwhelming inflation results or oversized pillows that embodied minimal rigidity, ensuring a best-fit spacing size was defined that promoted some degree of panel stiffness and aesthetic appeal.

Reaction-diffusion pattern test

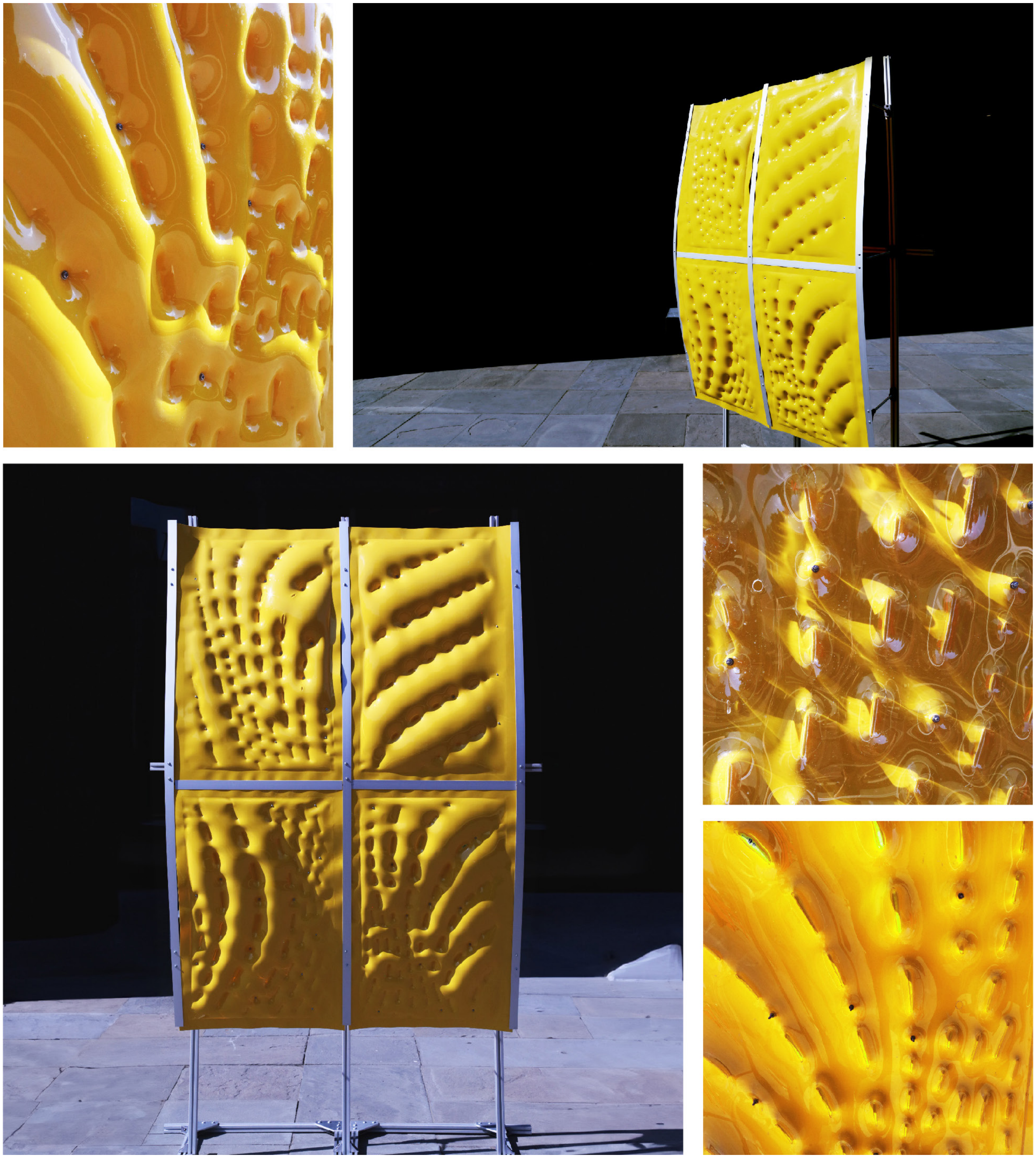
Based on the gradient pattern test, we used the Grey-Scott model reaction-diffusion pattern to explore complex possibilities for the varied effects that could be produced through different pattern scales and compositions (Figure 15). This allowed us to manipulate an initial pattern scale and test various inflation effects at multiple scales for different pattern gap dimensions. The pattern can be controlled to guide inflation as the smaller gap results in lesser inflations and larger pattern gaps inflates more. The self-organizing nature of the pattern allows for to create dynamic and adaptive aesthetic options. By adjusting the initial pattern scale and gap dimensions, it is possible to design surfaces that respond to environmental conditions. The Grey-Scott model's ability to generate diverse and complex patterns can thus be harnessed to create panels that are both functional and visually engaging.

Multi-Panel Prototype

An assembled prototype was produced to demonstrate the method's potential to embody variable aesthetic effects within a multi-panel assemblage. The prototype maintains coherence while introducing variability across four uniquely fabricated panels (Figure 16). The use of a frame in the forming process ensured edge profiling could be matched to enable alignment across panels, whilst the manufacturing approach produced extensive variation in each panel's inflated formation. Robot thermal welding of each sheet required 10-15 minutes, followed by 3 minutes for pneumatic thermoforming. The thermoforming process was comparable in time to other thermoforming methods suggesting the approach could gain industry traction if further developments in quality control and building envelope performance criteria were explored. The geometric flexibility in panel formation and the assembly ability to continue a pattern across several panels suggests that there is great potential in exploring this method for architectural design and manufacturing possibilities.

CONCLUSION

This research developed a variable pneumatic thermoforming method that eliminates the need for traditional molds in forming thermoplastic sheet-based panels. The technique involves robotic thermal welding and pneumatic thermoforming, allowing for the expansion of PETG sheets into unique, semi-rigid volumetric panels. A custom robotic thermal welding end-effector enabled accurate welding



16 Multi-part assembled prototype of Variable Pneumatic Thermoforming (top right). Part-to-whole pattern composition of four individual unique panels. Varied visual aesthetics presented by the use of two color of PETG sheets; frontal opaque view (top left) and back transparent effects (bottom right).

of sheets before inflation, while the developed material-physics simulation model enabled a relatively accurate prediction of manufacturing outcome, suitable for use in design-development activities before fabrication, enabling the overall approach to relatively easy to integrate into established design-to-production workflows. This was effectively demonstrated in the multi-part assembled prototype, where four unique panels produced a continuous complex-formed volumetric pattern of inflation. As a mono-material process, these volumetric panels are also completely recyclable, offering great potential benefits in applications such as building envelopes where lightness, stiffness, air cavities, and recyclability are beneficial. For such applications, however, other thermoplastics already in use for building applications, such as polycarbonate, may need to be investigated, and a range of building envelope performance criteria would need to be considered, as well as testing and evaluation of properties such as stiffness and flexural strength. As a proof of concept, however, this research demonstrates an exciting design and manufacturing workflow with great potential to author variable geometric parts within easily repeatable processes.

In considering possibilities for future industrialization of this method, the dimensions of the heating rig and robot platform constrain the maximum panel dimensions, limiting the overall size of volumetric parts. In addition to considering larger-size workcells with a larger robot and heating rig, research could be undertaken to explore a localized heating process or strategies explored to segment apart into several different heating zones that might allow a larger panel to be manufactured than the size limitations of the equipment, providing greater versatility and scalability. Refining the pneumatic control systems will also enhance the precision and reliability of the thermoforming process.

Variable Pneumatic Thermoforming: Robotic Thermal Welding for Volumetric Thermoplastic Building Envelope Panels offers the ability to rapidly form volumetric PETG panels into unique forms and to control the inflation sufficiently to produce patterns across an assembly of panels. This research advances digital fabrication practices in an architectural context by offering a unique design-to-production workflow that achieves varying aesthetic qualities in outcomes whilst its mono-material outcomes are fully recyclable It is hoped this research fosters more investigations into the possibilities of variably formed, fully recyclable thermoplastic envelopes. Whilst much research into performance evaluation for such applications is still needed, substantial benefits can be gained from this research that might inspire further architectural design creativity and closed-loop building life cycles.

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