Printflatables: Printing Human-scale, Functional and Dynamic Inflatable Objects

Harpreet Sareen*[1], Udayan Umapathi*[1], Patrick Shin[2], Yasuaki Kakehi[3], Jifei Ou[1], Pattie Maes[1], Hiroshi Ishii[1]

[1]MIT Media Lab
Cambridge MA 02139
USA
{sareen, udayan, jifei, pattie ishii }@media.mit.edu

[2]MIT Mechanical Engineering
Cambridge MA 02139
USA
pshin@mit.edu

[3]Keio University
5322, Endo, Fujisawa
Japan
ykakehi@sfc.keio.ac.jp

Figure 1. Inflatable objects fabricated by the Printflatables platform.

ABSTRACT

Printflatables is a design and fabrication system for human-scale, functional and dynamic inflatable objects. We use inextensible thermoplastic fabric as the raw material with the key principle of introducing folds and thermal sealing. Upon inflation, the sealed object takes the expected three dimensional shape. The workflow begins with the user specifying an intended 3D model which is decomposed to two dimensional fabrication geometry. This forms the input for a numerically controlled thermal contact iron that seals layers of thermoplastic fabric. In this paper, we discuss the system design in detail, the pneumatic primitives that this technique enables and merits of being able to make large, functional and dynamic pneumatic artifacts. We demonstrate the design output through multiple objects which could motivate fabrication of inflatable media and pressure-based interfaces.

Author Keywords

Human-Material Interaction; Shape changing; 3D printing; Digital Fabrication; Inflatables; Radical Atoms.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation : User Interfaces

*** The first two authors contributed equally to this work.**

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INTRODUCTION

In 1960s, architects and engineers introduced new fundamentals based on pressured air for lightweight, rapidly deployable and cost efficient structures. These included buildings, living environments, furniture, transport and other complex air-filled forms. The key to their popular use even today is in their scale and transformation characteristics. We draw inspiration from these properties of pneumatics and envision pneumatic environments where objects based on pressured air could work as morpho-functional artifacts around us. Printflatables is an attempt in this direction to enable fabrication of static and dynamic pneumatic forms at various scales.

Of late, the principles of pneumatics have been used in the field of soft robotics [15] to build physical agents [9] which conform to their surroundings and mimic biological actuation. One of the key focuses of soft robotics is on the kinematics and dynamics through material properties to enable interactions with unstructured environments. These structural composites [13, 36] and actuation principles [17, 18] have recently been demonstrated for shape changing interfaces in HCI [5, 39].

Inflatables uniquely afford large structures with transformation properties which is hard to match in terms of mechanics and scale in the rigid world. However, their manual fabrication is a complex process, especially so when dynamics come into picture. In our research process, we treat the structure of objects and their transformation as one, which allows us to print large objects in flat form, embed kinesis and automate their fabrication process.

Our system comprises of a design tool that decomposes three dimensional structures to inputs of two dimensional fabrication patterns and mountains (explained in detail later). These inputs are fed to a numerically controlled thermal contact iron moving on a three axis mechanical gantry. The printing process starts by rolling out textile from a spool. These textile layers are then passed through a modular attachment where mountains are made. The mountains (folds) are then furthered into a 800mm X 800mm work area where thermal sealing is performed. With the folds and sealed patterns along the length of membrane elements, the printed output then inflates to three dimensional shapes.

In this paper, we present techniques to transform flat membranes to three dimensional shapes through inflation. We then describe an automated fabrication process and a computational design tool as part of the pipeline. Finally, we highlight the size and actuation capabilities of our approach through multiple pop-up architecture and pneumatic bodyware examples.

Our main contributions include:

- design primitives that transform to three dimensions from flat shapes
- fabrication platform that prints in two dimensional form to produce pneumatic artifacts that transform in three dimensions
- fabrication-oriented computational design tool including parametric control of fabrication geometry and corresponding inflation simulation

RELATED WORK

Computational design

Computational design of inflation based objects has been proposed in the past. Plushie [19] and Furuta et al. [4] introduced a sketching interface for modeling plush objects which are simulated for inflation. Two dimensional piecewise patterns are then generated to match the simulated objects. The systems in [12] and [32] follow a similar approach of generating piecewise rest shapes from input three dimensional models with focus on seam placement for manual fabrication. However, both the systems require complicated manual fabrication which takes a long time. Piecewise assembly also removes a large number of possibilities of dynamics. We replace these piecewise assembly and manual methods with automated fabrication of unidirectionally angular structures. We also introduce dynamics in the simulation for fabrication of such objects.

Soft Robotics

The emerging field of soft robotics focuses on using soft materials for mobile machines which can accomplish tasks in natural environments. Rather than using rigid control systems, the focus is on the material properties and morphology of the bodies for actuation and dynamics. Elastomers [15], composites [13] and flexible materials [35] are mainly employed resulting in pliant structures. These concepts however do not directly scale to pneumatic structures such as furniture or bodyware such as orthotics where higher strength and lesser pliability is required. To enable force actuation and load bearing capabilities, our pneumatics employ quasi-inextensible fabric that exhibits less stretch and provides high strength at the same time.

Pneumatics Fabrication

The automated fabrication of pneumatics has remained constrained to only a few key soft mechanic components. Coulter and Ianakiev [3] proposed a 4-axis silicone printing system to fabricate tubular dielectric elastomers for use in biorobotic systems. Soft Lithography [29] employs printing, molding and embossing to fabricate 3D elastomers. Pouch motors [20] demonstrated fabrication of a class of pneumatic artificial muscles from sheet materials using heat stamping.

HCI

The principles of pneumatic actuation from soft robotics have been applied in the context of HCI for shape-changing interfaces. PneUI [5] and Sticky Actuators [22] introduced pneumatically-actuated soft structural composites and elastomers with integrated sensing. The elastomeric configurations and actuation enables only a class of shape-changing interfaces which are limited in size and strength they can exhibit. In addition, their fabrication is a lengthy and cumbersome process and not a general solution as the authors also mention. Niiyama et al [22] proposed soft planar actuators and their easy fabrication to animate everyday physical objects. Both PneUI[5] and Sticky Actuators [22] essentially enable actuation in their outputs and not the fabrication of objects themselves. When augmented on rigid physical objects, these solutions also require yielding points in the physical structure beforehand.

Aeromorph [24] is another project that focuses on fabrication of transforming inflatables with pneumatic hinges. They use stamping patterns to restrict inflation in certain areas which creates a bending effect. Such compressible hinges however limit the output structures to visible shape change without force exertion or load bearing capabilities. In contrast, the mountains form an incompressible part of our pneumatic structures resulting in implications of scale, force exertion and load bearing capacity for functional objects. We demonstrate these abilities and their significance through multiple examples in the sections ahead. The sensing techniques employed in Aeromorph and Printed Pneumatics [38] can potentially be applied to our pneumatics as well in the future.

On the basis of vacuumatics[10], Ou et al. [23] and Follmer et al. [6] showcased structures and interfaces based on negative pressure. JamSheets focuses on tunable stiffness of objects without an automated fabrication pipeline. The examples in their case are manually fabricated by sandwiching approximately 40 layers of fiber and using vacuum. Our technique on the other hand focuses on automated fabrication with two layers of fabric and actuation that is embedded in the structures for self-transformation.

MATERIAL

Commonly used inflatable furniture or portable architectural structures are made of flat membrane elements which assume complex shapes when pressurized. These are usually made with thick high strength plastic-backed fabrics or plastics and metal foils alone. Commonly available hot melt films are also utilized to give a heat sealable backing to textiles (nylon, silk) and paper [25]. For our inflatable structures where less pliancy or material deformation at maximal inflation is desired, we use membranes with high stiffness but negligible stretching strain. We used commonly available thermoplastic polyurethane (TPU) backed Oxford (200 Denier), Tafetta (100 Denier), Ether (70 Denier) and Nylon (70 Denier) fabrics. We were also able to use clear PVC (5-8 mil) sheets as a replacement of the above fabrics.

Thermoplastic bonding

Thermal sealing methods such as heat pressing with dyes [21] or creating seams with irons and rollers [34] are commonly used for manufacturing of inflatables in industries. In addition, ultrasonic and RF welders are also commonly employed for bonding thermoplastic films together. However, the fabrication process itself remains manual in most industrial processes [30, 14]. Owing to its wide availability and reduced complexity, we chose to automate the thermal bonding method with heated iron as discussed further.

AUTOMATED FABRICATION PLATFORM

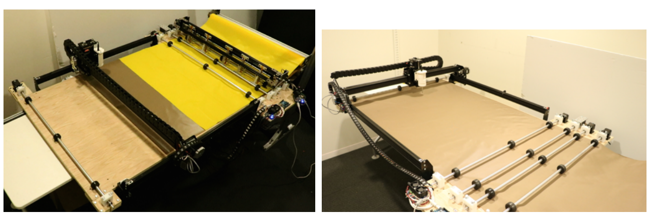

Figure 2. Custom CNC for fabric folding and sealing.

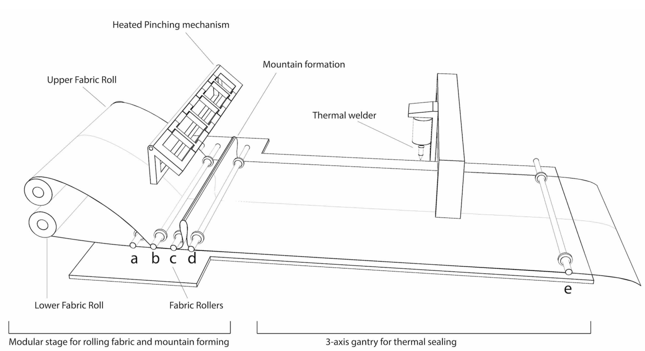

Figure 3. Overview of the machine

Figure 2 shows our custom CNC with mechanisms for feeding the fabric, introducing mountains and thermally sealing the fabric. Figure 3 is an overview of the various parts of the CNC. Our machine functions like an assembly-line with the following sequence: 1) Feed fabric from spool, 2) Form mountains, 3) Seal mountains, and 4) Perform 2D sealing and exit the fabric.

Step 1: Feed fabric from spool

Long spools of thermoplastic fabric were acquired (http://www.seattlefabrics.com/) and trimmed to a width of 760mm to fit within the machine work area. Two layers of

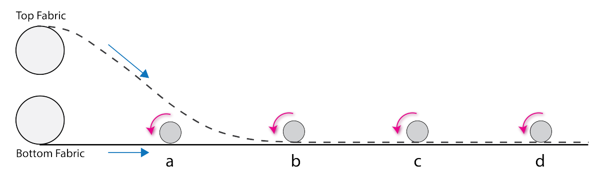

Figure 4. Step 1: Rollers a-d turn synchronously to feed the fabric

fabric are held in a spool dispenser. The dispenser has two bearing loaded rollers for friction-less unrolling of fabric. Fig. 4 shows how fabric is unrolled and fed to the machine. Rollers (a) and (b) are driven synchronously to pull fabric off the spool and feed two layers of fabric (top and bottom) into the machine. Note that roller (a) grips the bottom layer of fabric while roller (b) grips both top and bottom layer and feed them forward as they rotate. The bottom layer of fabric has the thermoplastic (TPU) coating facing up and the top layer has it facing down ensuring that the heat sealing results in maximum bond strength.

Step 2: Mountain formation

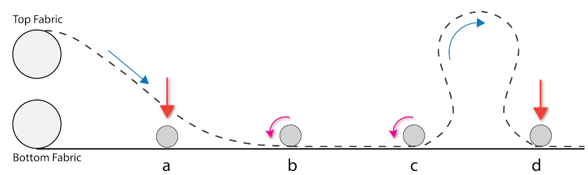

Figure 5. Step 2: Mountain formed between rollers c and d

One of the key techniques used in our fabrication technique is the introduction of folds in the top layer of fabric to create a difference in length between the two layers. The mountains are collectively formed by rollers (a), (b), (c) and (d) as in Fig. 5. Rollers (b) and (c) are driven synchronously while rollers (a) and (d) are held static. Although motors (a) and (d) are static, their drivers are actively engaged in braking position, thus clamping down the fabric. Rolling (b) and (c) alone slide the top layer while bottom layer is fixed. Since the fabric layers are clamped at (d), it accumulates between (c) and (d), forming a mountain-like structure.

Step 3: Sealing Mountain

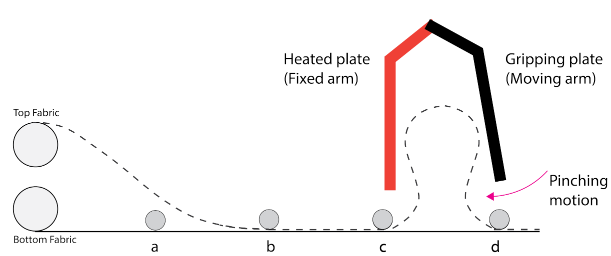

Figure 6. Step 3: Pincher's arm in motion to seal the mountain

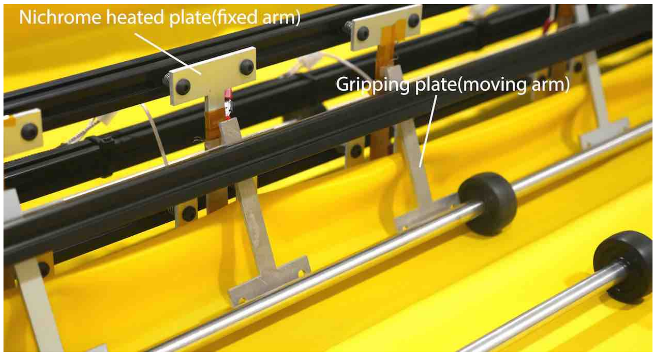

Figure 7. Pincher's Nichrome heated plate and gripping plate on moving arm

Figure 8. Pincher when in closed position seals mountain

Once a mountain is formed, it is heat sealed by a pinching mechanism. The pincher consists of a moving and a static arm, both carrying five equally spaced aluminum plates. The plates on the static arm are heated to 550F.

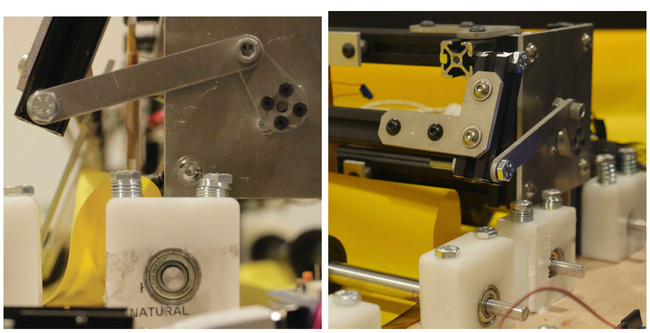

Figure 9. Mountain formed between rollers c and d

As in Fig. 9, the moving arm is driven by a rotary dc motor. This brings down the arm and pushes against the corresponding plates on the static arm. The pinching process is timed such that a bond is established between the two sides of fabric, thus keeping the mountain in shape for when it moves to the 2D sealing workspace.

Step 4: 2D Heat Sealing

A major chunk of our fabrication method uses simple 2D heat sealing. This is carried out by a standard 3-axis CNC gantry (Inventables XCarve) with a work area of 800mm X 800mm. The Z-axis of the CNC has a temperature controlled thermal sealing iron. The iron has machined tips for seal width of 5mm which is dragged over two or more layers of fabric for thermal welding. For seal widths greater than 5mm we do multiple passes with each pass offset from the previous. The z-axis mount is spring loaded to ensure consistent pressure during welding and to provide variable pressure as the thickness and the type of the material changes.

Once the mountains are sealed as in Step 3, the pincher arms are raised and all the rollers activate to allow the sealed mountain to pass through roller (d) and into the working area of the gantry to prepare for 2D sealing.

(a) 2D heat sealing on flat fabric

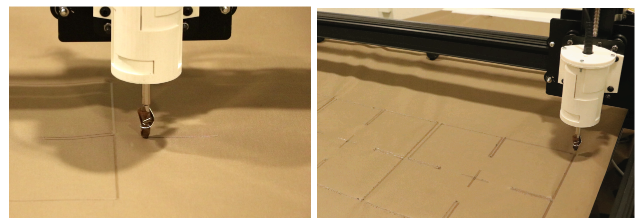

Figure 10. 2D thermal sealing of flat fabric.

Besides the mountains, 2D heat sealing on flat regions of fabric define the seams and in turn the three dimensional shape that the object will take on inflation. To create the seams the heated iron is dragged on two layers of fabric. The temperature of the iron, the pressure applied and the speed of movement are regulated to ensure consistent sealing and varies across materials as in Table 1.

(b) 2D heat sealing on mountain

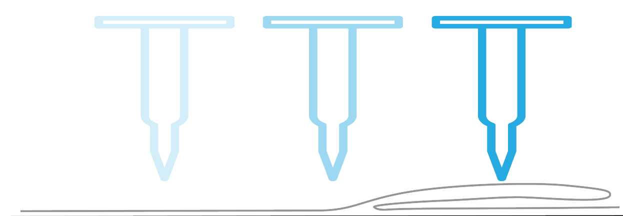

Figure 11. Heated iron going over mountain on 4 layers of fabric. This seals only top two layers.

The mountain sealing performed in Step 3 is only to bond the fabric to keep its shape temporarily. Once the mountain is in the 2D sealing area, the actual seams on the mountain are carried out by heat sealing. For this, the iron goes over the mountain as in Fig. 11. Although the iron goes over 4 layers of fabric, the temperature and pressure is regulated such that only the top two layers seal, hence sealing the mountain. Note that the region under the mountain is not sealed in the process. This unsealed region under the mountain may have to be sealed depending on the fabrication geometry of the object. For such a case where this region has to be sealed, after the iron crosses the mountain, it moves in the opposite direction to go over the unsealed flat fabric. This is similar to 2D sealing in Step 4(a).

Fabric	Temperature
Taffeta	430 F
Nylon	350 F
Pack Cloth	600 F
Oxford	500 F
Ether	350 F

Table 1. Temperatures for heat sealing the above materials with 0.1mm thickness TPU backing while thermal iron is traversed at 1 mm/s

Following the 2D sealing process, the fabricated object is pushed out of the 2D sealing area for post processing which involves cutting out excess fabric and manual insertion of air inlet valve.

Electronics

Motors

Our machine uses 7 stepper motors: one stepper motor each for rollers (a) - (e) (23HS22-2804s), and 3 motors for the X-Carve CNC gantry. We use two Arduino UNO microcontrollers with GRBL v5 shields to drive all the stepper motors. The pincher's linkage is driven by 2 DC motors (Pololu 227:1 Metal Gearmotor 25Dx56L mm) equipped with with quadrature encoders. These motors are driven by a Pololu Dual VNH5019 Motor Driver Arduino Shield.

Heating

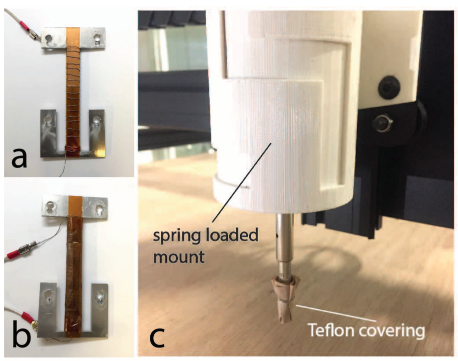

Figure 12. (a) Heated plate: Kapton and Nichrome, (b) Heated plate with Teflon wrapper, (c) Modified Weller solder tip with Teflon covering.

The pincher described in the Step 3 above uses heated plates on the fixed arm for sealing the mountain. These plates have an aluminum plate as its core. The plate is then wound by heat-resistant and insulating Kapton tape, followed by 24-gauge Nichrome wire. The Nichrome is then wrapped with a layer of Teflon. This ensures even distribution of heat for the fabric to not melt or leave any debris on the plates.

We re-purposed an off-the-shelf Weller WXP120 soldering iron with custom tips for 2D heat sealing. The tips are also wrapped with Teflon sheet for a smooth glide and to prevent the fabric leaving any debris on the iron.

BENDING ANGLE OF MOUNTAIN

Mathematical analysis

For the analysis, let us consider a single mountain of dimension ***w*** and ***h*** as shown in Fig. 13. A mountain is essentially

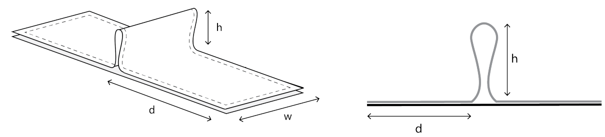

Figure 13. Mountain of height *h* and width *w*.

extra material introduced in the top layer of the sealed object (Fig. 14). Our analysis is under the condition:

$$d >> h \quad (1)$$

In our case, all the fabricated objects meet this condition. For the non-inflated state, the length of the fabric on the top surface is 2(***d***+***h***) and the length of fabric on bottom surface is 2***d***. Upon inflation, the object takes the shape as in Fig. 14. A planar section cutting along the object's length through it's center reveals that the length of the top surface is preserved(***2***(***d***+***h***)) even upon inflation (Fig. 15, 14). This is the result of the surface trying to maximize the volume due to the tension from inflation. Excluding the effect of inflation at the peripheries, we approximate the shape of an inflated objects as a cylinder with circular cross-section. With these assumptions, we analytically arrive at the bending angle as:

$$\theta = \pi * h/w \quad (2)$$

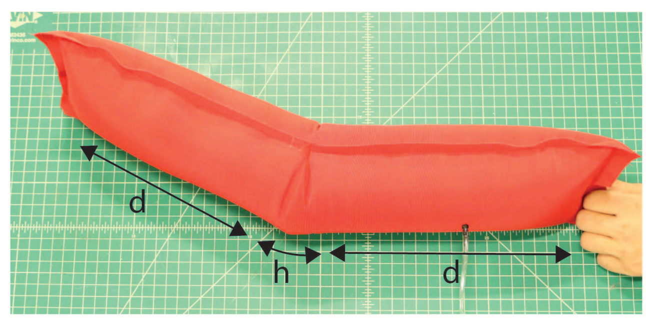

Figure 14. Single inflated mountain

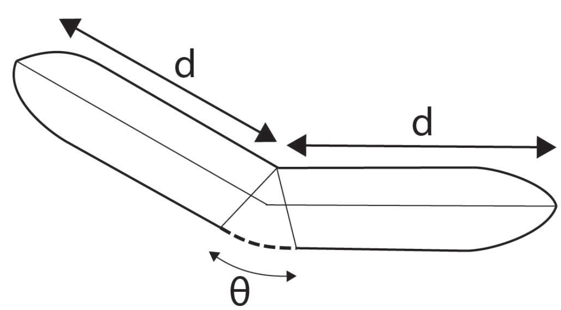

Figure 15. Cross section at the center along the length of the inflated object

Pincher's role in bending angle

Fig. 8 shows the five heated plates used in sealing the mountain. The distance between these plates determines the width ***w*** of the mountain. Hence for a given folding angle, the height ***h*** of the mountain can be computed from equation 2

Discrete Angular Folding

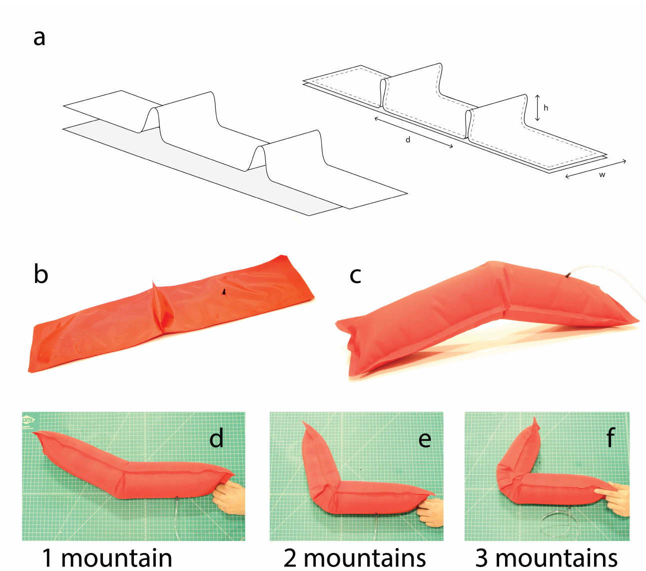

Figure 16. (a) Adding mountain in the upper layer for discrete angular fold, (b) Single mountain in uninflated state, (c) Single mountain in inflated state, (d)(e)(f) Folding angle increases with the number of mountains

Discrete bending angle is introduced in the fabricated object by forming mountains in the top layer of fabric using the rollers. The height ***h*** of the mountain has a direct correlation with the width ***w*** of the object as described previously in equation 2. Increasing the number of mountains as in figures 16 (a)(e)(f) gives us larger folding angle. Note that it is also possible to achieve large angles with a single mountain. However, we noticed that single large mountains usually tend to be weaker and tends to resist lesser loads.

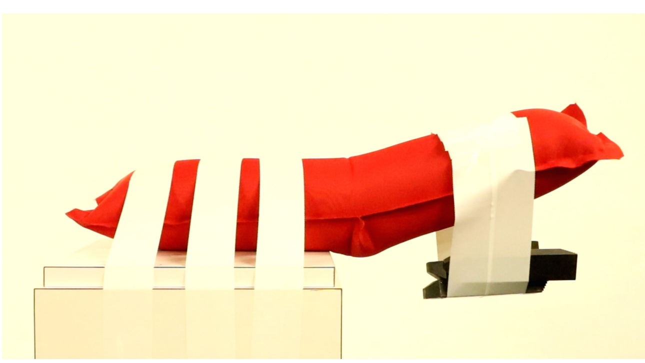

Figure 17. 7.5kg was required to fully straighten a 45 degree inflated object at 40psi pressure

We tested the strength of these folds by suspending weights at one end of an inflated tube folded at 45 degrees. This object was fabricated with 400 Denier Nylon pack cloth with the flat width between seams as 5 inches. The mountain height was kept at 1 inch for a fold angle of 45 degrees. With an inflation pressure of 40PSI, we found that an addition of 0.5 kg straightened the fold angle by 3 degrees. We were able to suspend 7.5kg before straightening out the bend completely. Thus the applied bending moment at this point was 75 kg-cm. We also found that the distribution of the mountains over a larger length increased the moment required to straighten the bend. These high forces at air pressures as low as 40PSI make it possible to perform actuation of human body parts such as arms and fingers.

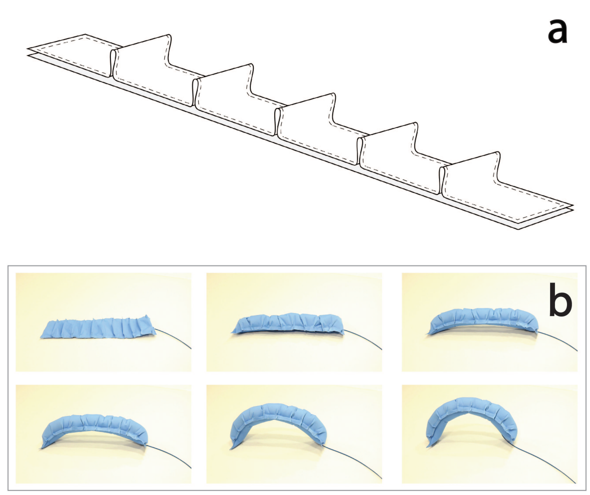

Figure 18. (a) Regularly spaced mountains and sealing, (b) Continuous bend upon inflation

Regularly spaced mountains

While sparse positioning of the mountains folds the fabric length in discrete angles, regular positioning of the mountains gives us continuous curves as shown in Fig. 18.

DESIGN AND SIMULATION PLATFORM

To inform and automate the design process of inflatables for the users, we developed an interactive Grasshopper [7] extension. Grasshopper is a parametric design tool tightly integrated with Rhinoceros allowing us to fully utilize the existing CAD and parametric design capabilities.

Workflow

The design workflow of Printflatables begins with the user modeling a new or importing an existing solid model (Fig. 19) in Rhino. They subsequently open Grasshopper and the Printflatables extension (Fig. 20). The extension initially prompts to select a solid model to flatten and the first and last outward surfaces for this model. It then parses this 3D model to produce a flattened two dimensional geometry.

We use this flattened geometry (Fig.19(b)) as our modelling reference to manually build another three dimensional model for the subsequent inflation simulation module. This module produces an inflation simulation that informs how the structure will inflate before beginning to heat seal the fabric. Once the simulated output matches the expected output, a GCode writer module is invoked by the user. This provides fabrication instructions for the machine to create the final inflatable object. The following sections explain the implementation of these processes in detail.

Step 1: Decomposing 3D to 2D geometries

The intended object to be fabricated is initially built by the user in Rhino. The soli geometry is decomposed to two dimensional geometry through a custom unroll operation as explained next. Unroll operation The unroll algorithm looks through the list of surfaces to identify common edges between them. A common edge between two surfaces share the same edge number in Grasshopper (Fig. 19(b)). With the help of these common edge numbers, an exploded and flattened planar skeleton from the solid model is extracted (Fig. 19(c)). The common edges are at points where the object has angular folds and hence we place mountains at these edges. This information about mountains is inserted in a new organizational layer in Rhino. It stores information pertaining to parameters of the mountain i.e. their height and number.

The number of mountains and the distance between them are parameterized with a relation to distribute the fold angle equally. To change these parameters, we built the user interface using the Human UI [37] extension of Grasshopper (Fig. 20b). The interface also allows to set number of constraint geometries (to prevent overinflation as a sphere) and their length. The final output from this setup is a two dimensional geometry that encodes information about fold angles.

Step 2: Inflation simulation

We currently simulate inflation of a model using Grasshopper's Kangaroo plugin [8]. Kangaroo is a physics engine for interactive simulation and form-finding. The user builds a three dimensional model using the flattened geometry as reference. This three dimensional model is then anchored with reference to a ground plane and provided inflation constraints through the options in Kangaroo. We use mesh relaxation techniques to simulate the soft fabric (Fig. 21a) and inflation physics to pressurize the internal volume. (Fig. 21b) shows the final output after running the inflation simulation.

Step 3: GCode generation and Communication module

The encoded 2D representation obtained from Step 1 is parsed with a custom Grasshopper GCode writer module (Fig. 22). This Grasshopper definition explodes the planar geometry into parts, traverses the geometry as per the routine in Fig. 23

The above procedure affords complete GCode for manufacturing an inflatable object. We use custom GCode fields for fabric feed (e.g: FF 400), engaging fold maker (e.g: MO 50) and exiting fabric from the machine. We implemented a Processing module which communicates via serial with the two 3-axis CNC controllers (Arduino Synthetos Gshield V5) on the machine. The module accepts the above GCode input file and executes the GCode line by line. It sends the normal GCode commands to the numerical control for the toolpath movement. It distributes the other commands to the second controller shield to engage the conveyor rollers, mountain-making roller and/or heat-sealing pincher.

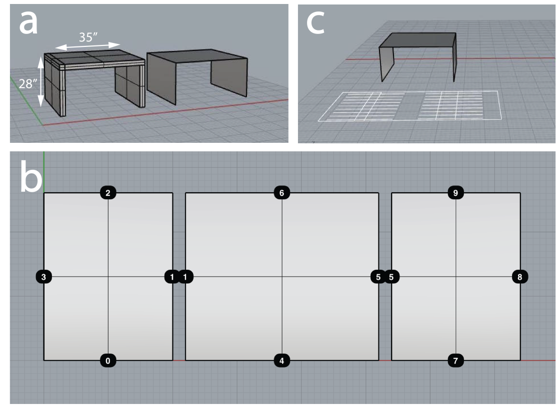

Figure 19. User interface to input 3D that user wants to fabricate.(a) 3D solid model, (b) Labeled edges for continuous surface extraction, (c) Flattened 2D geometry extracted from solid model.

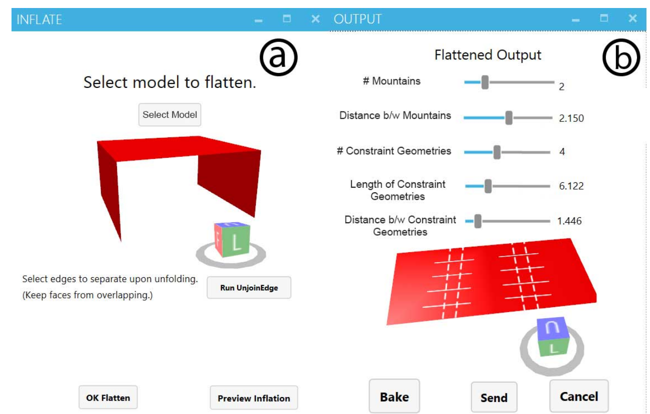

Figure 20. Skeleton extracted from an input three dimensional model for which a flattened fabrication geometry is subsequently generated

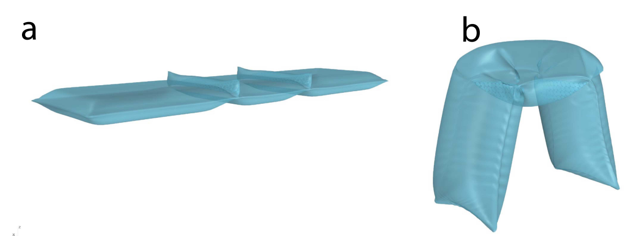

Figure 21. Inflation simulations for the input three dimensional models

2dsealing

APPLICATION EXAMPLES

To highlight the capability of our system, we demonstrate outputs through design examples across different size scales and force outputs.

Pop-up architecture

Fabrication of large scale rigid objects has been possible to some extent through subtractive fabrication. Soft objects on the other hand are primarily fabricated by casting elastomers in

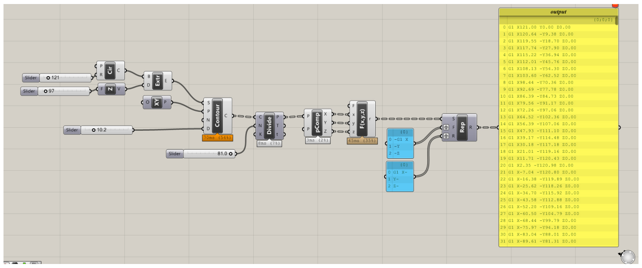

Figure 22. Custom GCode sequencer that traverses the flattened geometry to insert feed, fold and exit codes between the regular XY motion codes

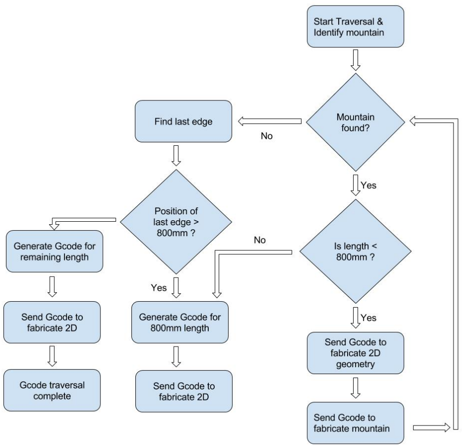

Figure 23. Gcode generation

3D printed molds [15] which limits the size for automated fabrication. In addition, pneumatic structures have been explored by architects and designers at large for pop-up buildings, furniture, decorative artifacts and displays [10]. These can be stored in a small space but inflated to large volumes in short times. However, fabricating such structures is a complex manual process. Our approach leans on baking fold transformations during the two dimensional printing process for the structures to inflate to expected shapes. Treating transformation and structure as one allows us to print large structures which has previously been difficult for automated fabrication of large pneumatic objects.

We created an inflatable chair using our approach with 200 Denier TPU-backed Oxford fabric. As shown in the image sequence (Fig. 24 a,b,c,d), the chair does a spiraling self-transformation from its flat shape on inflation. The spiraling transformation helps the chair to pack tightly and close the space for load bearing functions as shown in (Fig. 24f).

The structure has seven 90 degree folds that fold in the same direction. Each of these angular folds can either be done by a single mountain of large height or multiple mountains of small height. To have less buckling and higher strength in the structure (as explained in the Angular Folding section previously), we chose two mountains for each angle (i.e one mountain giving an angle of 45 degrees) instead of one large mountain. We chose the distance between these mountains as 25mm to spread them out and allow them to inflate fully.

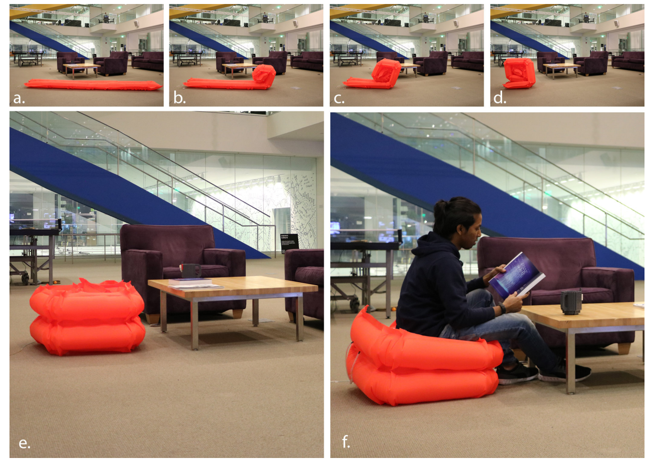

Figure 24. Inflatable chair designed and printed with Printflatables hardware and software pipeline

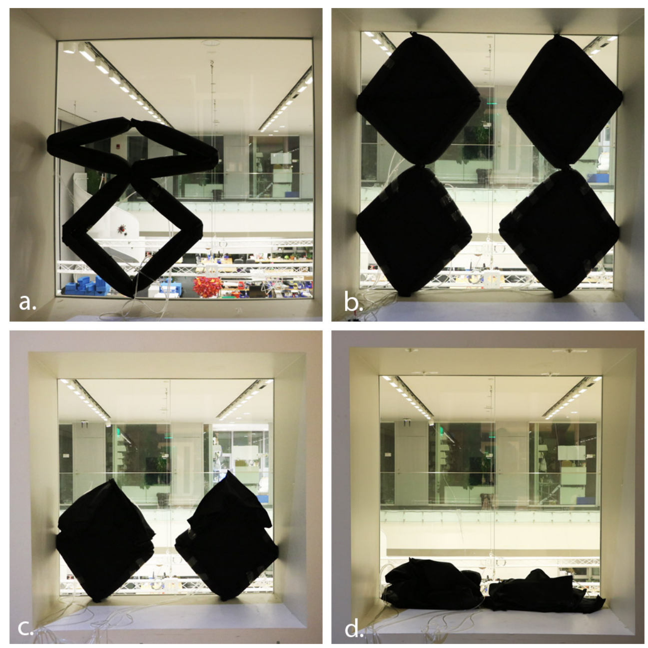

Figure 25. A responsive window blind that regulates the lighting in a room (a) Internal transforming elements shown in this image; (b), (c), (d) show different states when the structure is fully inflated, half inflated and fully deflated.

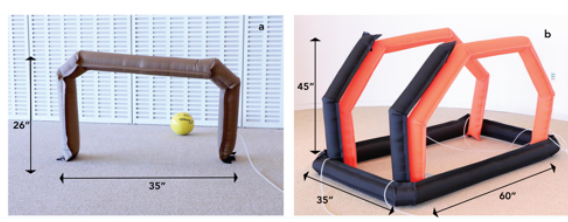

Figure 26. (a) Football goal post, (b) Car frame

Using these numeric inputs, our software extension parsed the geometry to flatten it to a 2D pattern and stored the fold position/angle information. This was then used to generate the GCode which was finally read by the Processing machine communication module . To begin with, 450mm of fabric slid in to the workspace. The rollers then engage to create the first mountain, temporarily seal the mountain and push fabric in the workspace till the next mountain. Subsequently, heat sealing of the boundaries is performed followed by creating another mountain and so on. In this process, the machine used 3m of fabric for each of the two layers.

The structure is removed from the machine by manually cutting it out with a scissors. The result was an inflatable chair as seen in Fig. 24 and is a functional load-bearing object. During the deflation process, we found the same object taking a different shape due to less strength in the folds and hence being able to serve as a couch. We believe that creating different chambers to activate different transformations can allow us to morph one object to the other. We explored this in another application, a responsive window blind Fig. 25 where the inflation deflation cycle is used to change the blind's shape for light regulation.

Fig. 25(a)) shows the blind's internal transforming elements which change their height on inflation. Each of these transforming elements was fabricated on the machine and joined together in a diamond shape. A stretchable spandex fabric is applied over each diamond for it to regulate the light when inflated. Each diamond's transforming elements are connected to a compressed air and vacuum inlets which are switched on and off using solenoid valves (McMaster Part No.5489T413) to inflate/deflate the diamond structures. Fig. 25 b, c, d show different states when the system is fully inflated, half inflated and fully deflated respectively. On a sun facing window, this regulates the lighting in the room automatically or as per personal requirements.

In addition to the above, to showcase the possibilities of the scale of fabricated objects, we also created multiple examples of large blow-up objects such as a football post and an inflatable car frame. (Fig. 26).

Bodyware

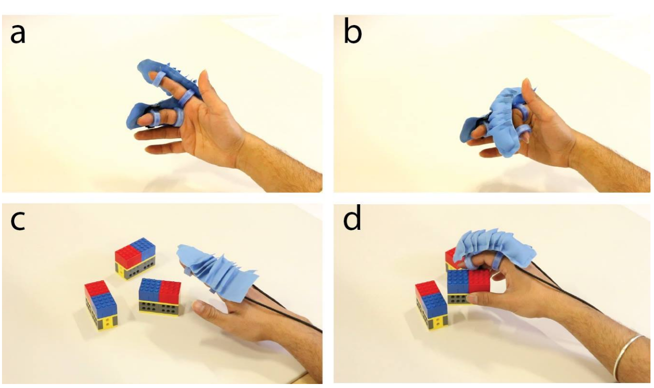

Figure 27. (a) Finger actuator with 3D printed rings, (b) Joint articulation with inflated finger actuator, (c)(d) Helping a user grab a physical object with the finger exoskeleton

Fabric based inflatables afford softness and malleability and are thus appropriate affordances for human interaction [1]. The idea of using inflated wearables has been explored in the past. XS Labs (2004) explored the idea of inflated clothing as way to extend personal space. On a commercial scale, CP Company introduced garments that inflate to become functional artifacts such as tents or mattresses [33]. Ixilabs created garments that convert into storage units and mats [16]. Samsonite Travel Pillow Jacket [1] contained an inflatable neck pillow for spur-of-the-moment naps [2]. Hovding showcased an airbag for cyclists [11]. Other examples include Awakened Apparel [25], Inflatable Collar [33] and Walking City dress [31].

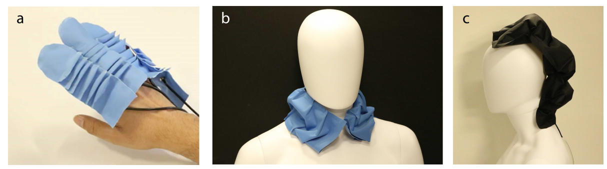

Figure 28. (a) Finger actuation, (b) Inflatable neck strap, (c) Inflatable protective airbag for cyclists

On the other hand, the on-body inflatable orthotics generate forces adequate for actuating body parts [28]. To demonstrate the fabrication of such objects, we printed multiple on-body pneumatics and force-actuation devices as an example. These include a single joint articulation soft exoskeleton, a finger actuation device, an inflatable neck support and protective bike airbag.

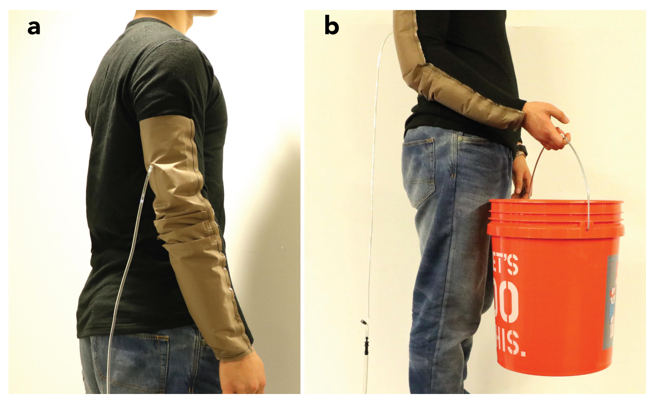

Figure 29. (a) Person wearing inflatable exoskeleton. (b) Arm actuation through inflation

Soft finger actuators have previously been shown by various groups [28], [27], [26]. We attempted to fabricate one such soft actuator (Fig. 27) with thermoplastic fabric on our platform. The aim was to print a conformable finger exoskeleton with joint articulation at two positions. We modeled the actuator in Rhino as it would appear in its final position and imported it in the Printflatables extension. The exoskeleton has folds of 90 degrees each at two positions. For each angular fold, we spread three mountains as per our finger joint length. The flat geometry generated with the extension is then fed to the Processing communication module which then starts the machine conveyor rollers and heat sealing fabrication.

The smallest height of mountains formed by the rollers that is heat sealable is currently limited to 0.25 inches. This was the height for each of the three mountains mountains per angular fold which also allowed us full joint articulation. We mounted two layers of soft TPU Ether Fabric (0.1mm TPU coating, www.perfectex.com) for fabricating this object. 101.6 mm of top and bottom layer fabric was used in the fabrication process. We cut out the final output from the fabric manually and glued 3D printed rings at the joint positions (Fig. 27a). Multiple actuators were fabricated in this fashion as shown in Fig. 28a. Upon inflation (max. 20 PSI), the finger starts bending at the joint positions (Fig. 27b) which allows a person to grasp/pickup an object as they approach one (Fig. 27c, 27d). We used an electro-pneumatic regulator (ITV2050, SMC Pneumatics) to regulate the air supply and bending pressure. Better control systems can be achieved with separate channels for each joint in a rehabilitative application. The design of such pressure-actuated devices can be modeled easily through our platform while observing the joint articulation and print specific medical orthotics.

In addition to the finger actuator, we designed and fabricated a conformable exoskeleton with multiple segmented folds to produce single joint articulation (Fig. 29) by spreading across a participant's elbow. The exoskeleton was then printed and integrated into a regular t-shirt by sewing. A benefit of using our mountain actuators is that it allows the design of conformable objects, e.g: exoskeletons with minimal sheet form factor that integrate into normal clothing and disappear when not required. To test the performance, we mounted the exoskeleton on a mannequin and evaluated flexion loads with 1,2 and 3 mountain actuators (Fig. 29 d,e,f) individually at 40PSI. The premilinary results for flexion loads were 9kg, 13kg and 15kg respectively. By varying the pressure through inflation (40PSI - 100PSI), all five participants reported expending less effort in picking up a load (5kg) than without an exoskeleton.

The other class of fabricated objects included an inflatable neck strap (Fig. 28(b)), a bicycle protective airbag (Fig. 28(c)) and an active baby pillow. We believe that a range of examples suggested from past works on pneumatic wearables and toys are made possible for automated fabrication through our printer. One such preliminary investigation was a caterpillar toy as shown in Fig. 30. The fabricated actuator legs were stitched onto a rigid body and connected to inflation deflation switching solenoid valves. On changing the air cycles from the front legs to back and so on, the soft robot moves forward. We believe such possibilities of automated fabrication of robots at various scales from our platform is promising and can be used to construct functional pneumatic robots for various tasks in the future.

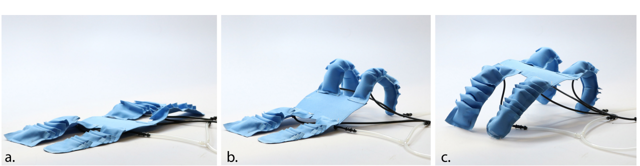

Figure 30. A soft caterpillar toy that moves forward with inflation deflation cycling through front back legs

LIMITATIONS AND FUTURE WORK

- The current implementation of the machine restricts folding of the fabric to a single direction. However, we plan to further improve our mechanical implementation for creating more versatile folds in the fabric and hence more control over bending angle.
- For high denier fabrics, thermal welding is not a foolproof method for sealing and creating seams. In the future, we would like to explore RF and Ultrasonic sealing methods for robustness in the seams.
- Once the printing process has ended, removal of extra fabric material is needed which can be automated later with a tool change for cutting. Insertion of an air inlet valve for inflation is done a posteriori.
- The inflation simulation for objects requires manual intervention by the user in our current software tool. We intend to streamline and incorporate the simulation as an automated process in the software pipeline in the future.
- Our current heat sealing technique enables to selectively seal only the top two layers. We intend to exploit this further in fabrication of layered pneumatics and expand the design space.

CONCLUSION

We presented techniques to transform 2D rest shape objects to 3D forms through shape tranformation. Our fabrication platform creates folds along the length of the thermoplastic fabric using thermal welding. The user designs or inputs the three dimensional model through a custom Grasshopper plugin to get fabrication geometry and inflation simulation. The fabricated objects can be of human-scale and demonstrate high force actuation. To validate this, applications around pop-up architecture and body augmentation with soft wearables were shown.

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