A New Manufacturing Process for Soft Robots and Soft/Rigid Hybrid Robots

Hee Doo Yang and Alan T. Asbeck

Abstract— **We present a novel manufacturing process for creating monolithic, multi-chambered inflatable structures including both soft and rigid components. Specifically, our process involves stacking layers of textiles or plastics and thermal adhesive film, then bonding the structure with a heat press or in an oven. Several different ways of arranging textiles and thermal adhesive film in order to achieve airtight structures are presented. Since this process only uses materials that bend, but do not stretch, it permits the easy inclusion of rigid structures such as circuit boards, plates that constrain inflatable chambers to bend in specified locations, and rigid pieces that enable sections of a robot to be connected in a modular fashion. Additionally, the process permits folding layers before their assembly, leading to more complex geometries. We present three different possible seam types, and enumerate the different types of corners that can be constructed without leaking. We present measurements of the ability of these structures to support pressure and measurements of the strength of bonds between textiles and other materials. Finally, we present two examples of robots constructed using this manufacturing method, including a hybrid soft/rigid robotic arm and a soft robot that can roll along the ground.**

I. Introduction

While research in soft robotics spans decades, in the past several years it has accelerated rapidly. This is due in part to the potential benefits of soft robots, including their light weight, intrinsic compliance, and relatively low cost. Tasks that require safe interaction with humans, complex or delicate object manipulation, operation in complex and changing environments, or mobility in unstructured environments are in principle better suited for soft robotic systems rather than those constructed from stiff materials [1], [2].

Despite these benefits, there are still a number of opportunities for improvement in the construction and use of soft robots. They can be difficult to control, in part due to their frequently having few embedded sensors. While the robots are inexpensive, in many cases they can require a time-consuming and complex process to manufacture. For silicone-based soft robots that can stretch, special structures may be required to interface with rigid or inextensible objects to avoid stress concentrations. Following is a brief review of prior work in the area of soft robots, illuminating several of these current challenges in more detail.

Many existing soft robots are made of silicone rubber, PDMS, or other types of rubber [1]–[7]. These materials allow the robots to stretch with high strains, enabling them to expand or contract in multiple dimensions during inflation or deflation. To construct rubber-based robots, liquid rubber is poured into a custom 3D mold that is often fabricated using a 3D printer. To generate enclosed volumes, as is necessary to build pneumatic chambers, for example, several molding steps are usually required [5], [6]. While interesting structures can be made in this way, the manufacturing process can be very complex, requiring multiple embed-cast-cure cycles that are time-consuming. If the robot geometry is changed, new molds must be fabricated.

Additionally, the extensible nature of silicone-based robots presents a number of other challenges. Off-the-shelf sensors, wires, plates for mounting objects, and circuit boards are all inflexible in at least one dimension. To interface with these, several layers of material of intermediate stiffness have been used to avoid stress concentrations and delamination at the soft-rigid interface [8], [9]. Other groups have spent much effort coming up with sensors or wires that can stretch, typically using a liquid metal flowing through channels in the material [8], [10]–[14].

A second class of soft robots is those formed of thin plastics or coated textiles that are impermeable to air. These are then bonded together in a heat sealing process or a welding process, using a thermal adhesive film to bond different layers together or melting them together. A number of groups have formed pouch-like structures by heat-sealing two layers of plastic or coated fabric together to form a series of chambers [15]–[24]. These structures are comprised of small pouches or larger chambers that have the ability to bend out of plane, incorporate simple pinch folds, and attach to surrounding rigid plates. These can be used as actuators if they are made to shrink in one dimension or bend when inflated. Some robots use several pieces of vinyl-coated fabric to make large robotic structures [25]. Additionally, if a "skeleton" in a zig-zag shape is enclosed in a pouch, it can be made to curl in a specified manner under vacuum [26]. In addition, other structures have been formed from heat-sealing or sewing a pocket out of cloth, and then using a separate airtight chamber inside to hold the air [27], [28]. In each of these cases, the resulting structures have been limited to using two layers of material, and thus creating single pouch structures.

Also, some groups have made structures out of long tubes of thin plastic, including Vine robots [29] and others [30]. Still other groups have made bellows actuators, which have a high extension ratio [31]–[33]. To manufacture these, a complex

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Fig. 1. A soft/rigid hybrid pneumatic robot arm made with the manufacturing process described in this paper.

process was required, in some cases using a CO_2 laser to cut the materials or custom welding electrodes to join them.

In this paper we propose a novel manufacturing method for centimeter-scale to meter-scale soft robots that enables the creation of a wide range of structures with embedded wires and electronics (Figures 1,2). The process involves stacking layers of thin, inextensible materials, interleaving them with sheets of thermal adhesive film, then bonding them together using a heat press, ordinary household iron, or oven. This results in a structure with one or more interconnected chambers, which expand into an airtight, three-dimensional shape when inflated. The manufacturing process allows for the inclusion of embedded sensors on every surface of the robot, such as force sensors on the robot's exterior or pressure or displacement sensors on the interior of the robot (thereby making them intrinsically waterproof). Finally, if the sheets of material are folded before being stacked and bonded to each other, very complex shapes can be created.

Our approach provides several benefits: (i) since no mold is required, it is possible to fabricate new designs quickly and cheaply once they are designed; (ii) since material is added to the structure in layers, it is easy to incorporate sensors and various semi-rigid or rigid materials such as circuit boards, pneumatic tubing, or structural components during the manufacturing process; moreover, (iii) since the layers deform by bending and do not stretch, rigid elements can remain bonded to the robot as it deforms with minimal stress concentrations.

While other groups have used related manufacturing processes, our proposed method is simple and allows for a wide range of new actuated geometries, including chambers that inflate into three-dimensional prisms (Figure 2C) and multi-layer bellows actuators that curl when inflated (Figure 2D). These forms can readily be combined into more complex structures with our method.

In the remainder of this paper, we first provide an overview of our manufacturing process (Section II), then discuss three different ways of assembling the layers and how corners and rigid structures can be included (Section III). We then present some measurements on the resulting structures (Section IV) and some examples of robots built with the manufacturing process (Section V) before concluding.

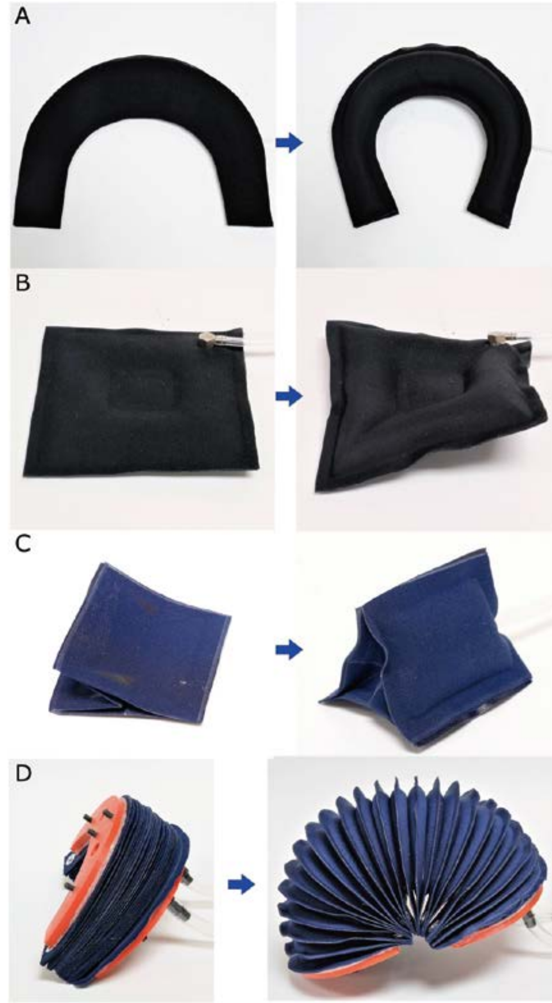

Fig. 2. Soft actuators made by the manufacturing processes described in this paper. A, crescent-shaped chamber that curls inward when inflated; B, square pouch that twists out of the plane when inflated; C, chamber in the shape of a triangular prism; and D, bellows structure formed of crescent shapes that curls when inflated.

II. Overview

Our fabrication method for inflatable robots uses sheets of a thin material such as a textile or plastic film combined with a thermal adhesive film. In this paper we focus on using textiles as the layer material, but the process is equally applicable to plastic films. The process has several essential elements. First, the materials are cut to desired shapes. Second, when textiles are used as the structural elements, they must be made air-impermeable by coating them with a layer of thermal adhesive film. Next, the materials are arranged in a stack, and heated while under pressure. This particular step can be done iteratively, bonding a few layers at a time with a heat press or household iron. Alternatively, the entire structure can be bonded at once by clamping the materials together and placing them in an oven. Complex structures are formed through the appropriate arrangement of thermal adhesive film and holes in the layers, as explained in subsequent sections.

In Section III.A we provide more detail on the materials used with this process, and in Section III.B we present two different methods for assembling these structures, which we call Type I, II, and two different ways for bonding these materials: a heat press machine or a convection oven. These differ in how the layers of textile are coated in thermal adhesive film to make them air-impermeable, and how the structures are heated and pressed. In Section III.C, we discuss bonding textiles to rigid structures, for which it is possible to use a different type of thermal adhesive. Finally, in Section III.D, we discuss the different types of corners that can be created and which lead to the resulting structures being airtight.

III. Manufacturing Process Detail

A. Materials

The core of our process is a thermoplastic polyurethane (TPU) film (#HM65-PA, Perfectex LLC.), which serves in two different roles. First, it acts as an adhesive between different layers of material, bonding structures together around their edges or centers, and bonding rigid materials to the layers. Second, it acts to make textiles air-impermeable. We have found using a film with thickness of 0.1mm thickness leads to the best outcomes for both applications of bonding as compared to thinner films.

The next portion of the structure is a thin layer such as a plastic film or a textile. We have primarily focused on using textiles as the structural layers, due to their resistance to creasing, their resistance to stretching, and their high tensile strength as compared to plastic films. When selecting a textile, using a thin fabric is best to maximize the flexibility of each layer, especially if two layers of fabric are bonded together such as occurs at seams and with Manufacturing Type I (Section III.B). However, if the textile is too thin, it may not have the required tensile strength to support high pressures. We have found a medium-weight Poplin fabric (65% polyester, 35% cotton) provides a good ratio of strength to thickness.

Finally, rigid structures can be incorporated into the robots, thereby making hybrid soft/rigid robots. The rigid structures can be attached at the ends, for example to mount an inflatable robot arm to a wheeled platform, or they can be incorporated throughout the robot. Some examples of the rigid elements that could be incorporated include circuit boards containing sensors, rigid segments that constrain the shape of the inflated chambers, or rigid end pieces that allow the robots to be modularly connected and disconnected. It is possible to use a variety of materials as these rigid structures, including plastics or other types of rubber.

B. Layered Manufacturing Methods

We present two different methods for interleaving the TPU film and textile, and two methods for heating and pressing the structures, each of which has its own benefits.

The first method (Type I) uses a sandwich of textile-TPU film-textile to make the fabric airtight, and a heat press machine or household iron to bond the structure in layers. First, the materials are prepared for assembly (Figure 3). Large sheets of fabric are made to be airtight by placing a layer of TPU film in between two layers of fabric, and placing the

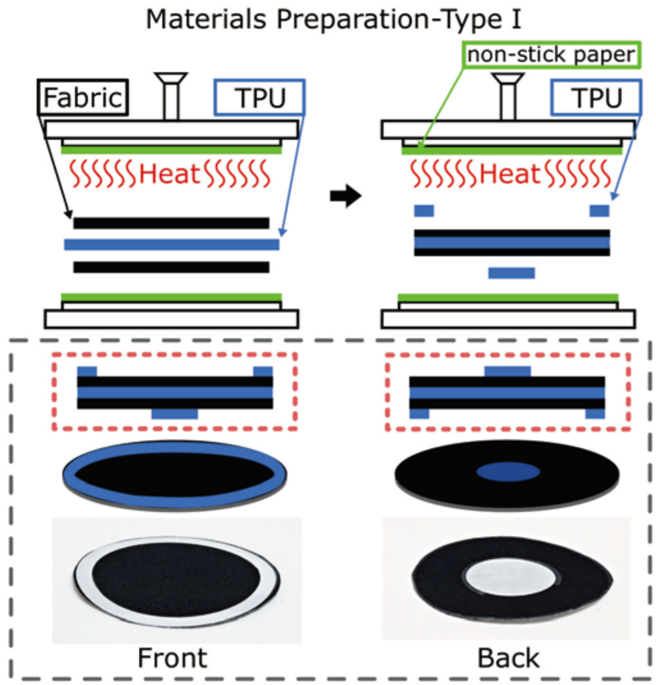

Fig. 3. Material preparation for the first type of layered manufacturing. In this and in subsequent figures, a side view is shown of the heat press with materials inside. The heat press is then clamped down to bond the materials under heat and pressure. The lower half of the figure depicts a cross-section view of the assembled structures, in addition to photos of some pieces that were fabricated.

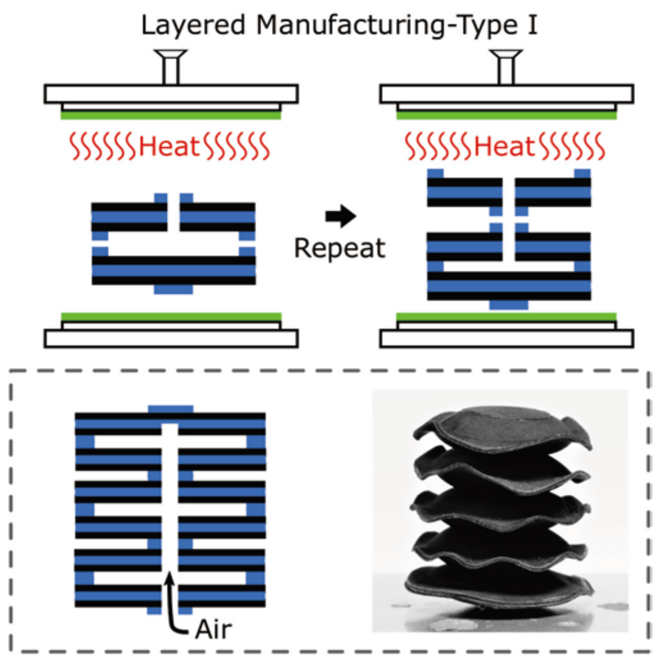

Fig. 4. Assembly of the pieces in the first type of the proposed layered manufacturing.

stack in the heat press machine at 154°C (310°F) for 60 seconds. After the fabric is laminated in this way, shapes can be cut out with a vinyl cutter machine or scissors. Additional layers of TPU film are also cut to a desired pattern, and placed on top of or below pieces of the laminated fabric. The pieces are aligned with each other by hand. These are then bonded in the heat press machine at 154°C (310°F) for 20 seconds. A

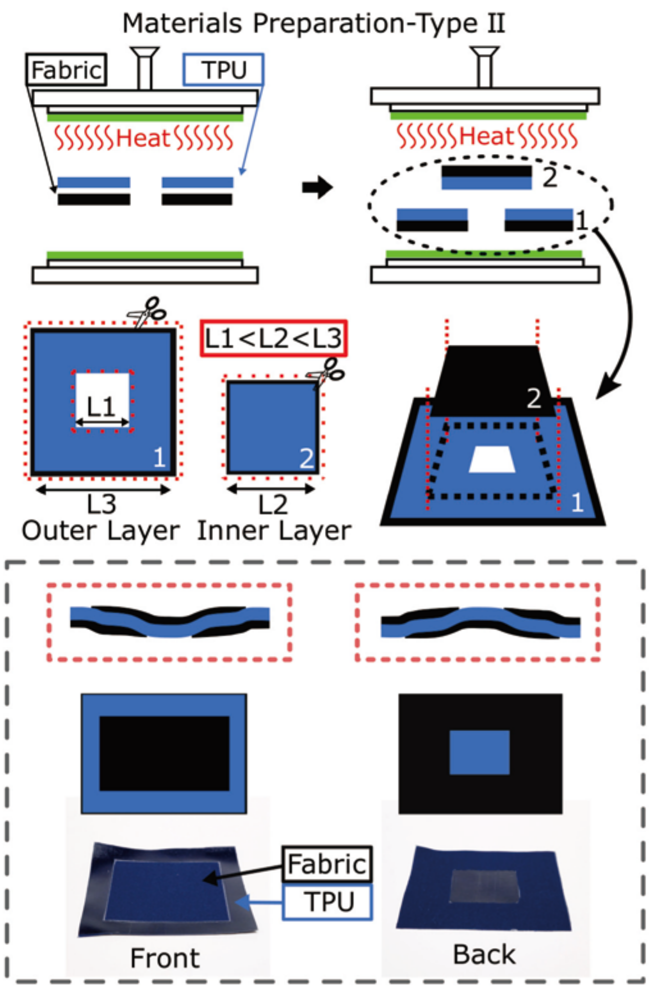

Fig. 5. Material preparation for the second type of layered manufacturing.

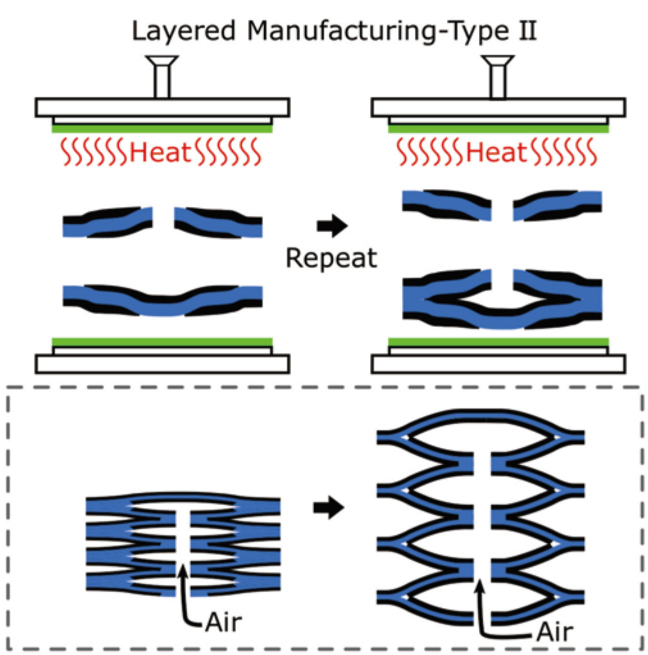

Fig. 6. Assembly of the pieces for the second type of manufacturing.

layer of non-stick paper that comes with the TPU film prevents the structure from bonding to the heat press. After the patterned fabric-film-fabric sandwiches are prepared, the final shape is constructed from the bottom up, by placing a new layer on the structure, bonding it with the heat press machine at 154°C (310°F) for 20 seconds, and then repeating for the rest of the layers in the structure (Figure 4). This iterative process is necessary because the heat press machine only applies heat at the top surface; it is also possible to bond a few layers at a time with a longer duration in the heat press machine. On both the top and bottom surfaces, a 1cm silicone pad conforms to the shape of the structure, pressing the different layers against each other even if they are of different thicknesses. Notably, this only accommodates relatively small (<0.5cm) differences in height; removable spacers placed underneath some of the lower layers can be used to equalize height differences and ensure an equal heat distribution across the top surface.

With this construction, it is relatively fast to create shapes and bond them because the process to laminate the fabric can be done in large sheets. However, the final structures are not perfectly airtight. As can be seen in Figure 4, the thermal adhesive film prevents air from flowing perpendicularly through the fabric, but air can still escape through the fabric itself in the edges of the structure, in between the adhesive layers. This leads to a continuous, slow leak in structures built this way, where a structure similar to the one in Figure 4 (6cm diameter, 15cm tall, 5 segments) will deflate in approximately 5 minutes with a load of 10N on top.

The next proposed method (Type II) shares the same manufacturing process of using a heat press as Type I, but uses a different way of preparing the materials to ensure the resulting structures are completely airtight. First, pieces of fabric that are coated with a TPU film on one side are prepared as in Figure 5. Instead of forming a sandwich with fabric-TPU film-fabric as in the Type I process, the fabric is cut into an "outer" layer with the TPU facing up, and an "inner" layer which is flipped upside down so it has the TPU film facing downward. The outer layer is assumed to have its outer edge of side length L3, and it has a hole in it of side length L1. The inner layer will have the same overall shape as the outer layer, but with its outer side dimension L2 a little smaller than that of the outer layer (L1 < L2 < L3). The hole in the outer layer will serve to bond this section of the robot to an adjacent section. Next, the outer and inner layers are aligned, and clamped together in the heat press machine at 154°C (310°F) for 60 seconds. This results in a structure which in essence has a continuous layer of TPU film through its center, but with textiles covering portions of it on the top and the bottom. The exposed portions of the TPU film are used to bond to adjacent layers in order to make a continuous layer of TPU film throughout the entire structure, thereby making it airtight. Starting with the pieces of bonded TPU film and fabric, the rest of the assembly process is shown in Figure 6, where the layers are stacked and bonded individually as they are in the Type I manufacturing process.

Compared to the Type I manufacturing method, this Type II process is somewhat slower due to the additional steps in cutting material, arranging it, and bonding it in the heat press. However, the resulting structure is completely airtight (see Table I).

The last proposed method (Baking) uses a convection oven instead of a heat press, and can use the arrangement of fabric

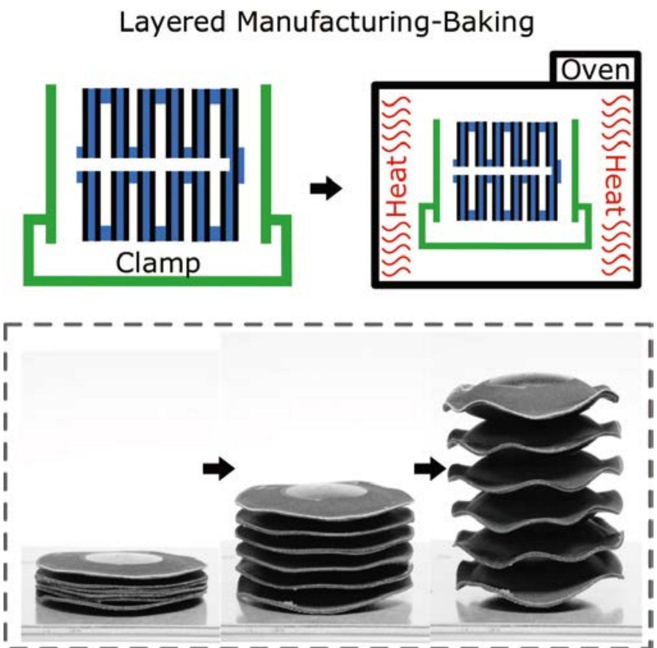

Fig. 7. The second assembly method, where an entire soft actuator or robot is bonded simultaneously in an oven.

and TPU film from either Type I or II. In this method (Figure 7), the materials are cut and then all of the materials for the entire structure are placed in a large stack. The stack is clamped together with a C-clamp and metal plates on each end, and then baked in a convection oven at 177°C (350°F) for 15 minutes (baking time varies depending on how many fabric layers will be bonded together at once). The last method is the easiest way to build soft robots compared to the previous processes. However, the size of the robots may be limited, as the entire structure must fit inside an oven; for comparison, with the previous methods, small portions of the structure can be bonded in sequence if the entire structure does not fit on the heat press machine all at once.

TABLE I COMPARISON OF MANUFACTURING PROCESS OPTIONS

Type	Advantages	Disadvantages
I	• Fast material preparation process	• Actuators are not perfectly airtight
II	• Actuators are perfectly airtight	• Slow material preparation process
Baking	• All types of material preparation can be used • Completed robots can be made in one-step process	• Robot size limited by oven size

C. *Inclusion of rigid surfaces*

Rigid surfaces can be included at any stage of the manufacturing process. One possibility this provides is the ability to create a "frame" in a pneumatic robot or actuator. A single enclosed pouch will tend to have a smoothly-curved shape when inflated. However, flat segments with intervening sharp corners can be constructed by bonding rigid materials to the inside or outside of a pouch (Figure 8) with the TPU film. Following the results of our materials testing (Section IV), the best materials to use for these rigid segments are ABS plastic and PVC plastic.

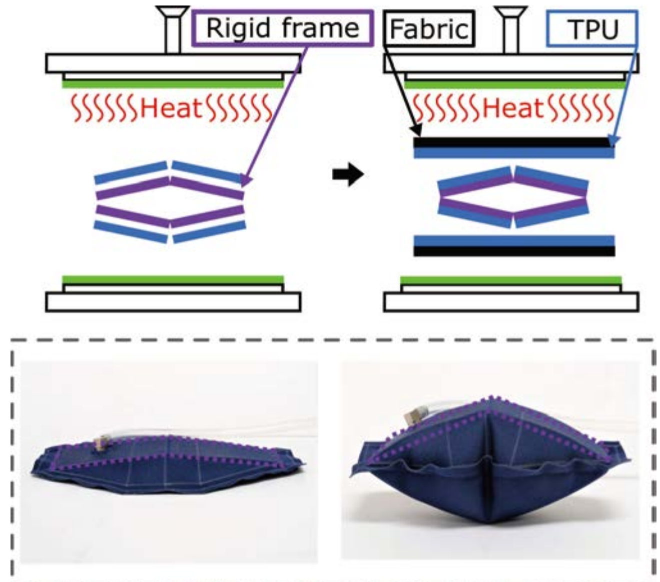

Fig. 8. Manufacturing process to create a frame in a soft actuator.

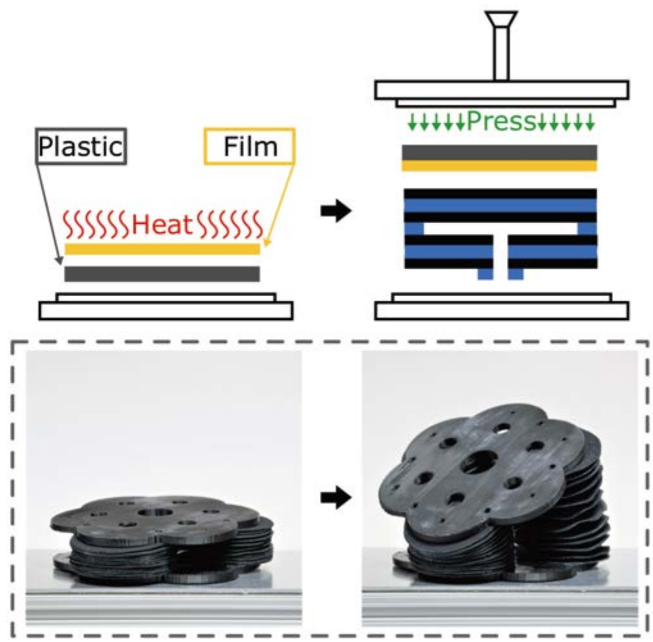

Fig. 9. Manufacturing process with Fastel film to bond soft and rough rigid surfaces. Here, a 3D printed plate is bonded to three bellows structures next to each other. The structure shown is one of the actuated segments in the robotic arm in Figures 1 and 13.

An additional manufacturing process is introduced in Figure 9, to bond pieces of plastic that are not smooth. Specifically, ABS structures can be built with a 3D printer. However, with a low-quality 3D printer, the resulting parts are slightly rough; this prevents a single layer of TPU film from bonding to them with its full strength. Several layers of TPU film can be used to accommodate the surface roughness. Or, a different thermal adhesive film can be used: Fastelfilm 20093 (Fastel Adhesive and Substrate Products, Inc.). To use this, the film is first pre-heated on the ABS surfaces (e.g. with a heat gun or heat press), then the ABS part and a soft robot component are aligned, clamped, and bonded in the press machine. Heating the film before clamping it in a press (without heat) is necessary if the ABS parts are thick, since thick parts prevent heat from flowing through them to the adhesive layer if placed in the heat press as usual. Importantly, the Fastel film is somewhat thicker than the TPU film (0.25mm instead of 0.1mm), and becomes a liquid when heated, allowing it to flow into crevices. This works well for bonding rough structures, but does not work as a replacement for the TPU film in the normal manufacturing process because the liquid flows in an unconstrained manner and glues the layers together in undesirable locations. For comparison, the TPU film acts more like a gel when heated, thereby staying in place on the fabric.

In this manner, rigid surfaces can be used to connect different pieces of a robot with conventional fasteners. The robotic arm in Figure 1 has several soft segments, each of which has a 3D printed end piece, and then these segments are secured to each other with nuts and bolts. This enables the robot to be easily disassembled for repair or re-configured. In addition, rigid body parts help to integrate sensors into soft robots directly. For example, IMUs and pressure sensors can be integrated into a rigid structure, then the structure is placed in the middle of a soft robot. Off-the-shelf pressure sensors can allow sensing a chamber's pressure, and IMUs embedded in soft robots can be used for their control, since with them a segment angle can be determined to within a degree.

D. *Corners*

A wide range of robot topologies are possible with the inclusion of folds and corners in a soft layered robot. Three types of seam constructions are introduced in Figure 10. While in the manufacturing methods described previously all of the layers had their seams on the exterior of the structure (OUT in Figure 10), two other seam constructions are possible if folds are permitted. An IN fold is similar to an OUT fold, except with the seam on the interior of the robot. A 180° fold requires one piece of fabric to be folded, while the other is straight.

By folding adjoining pieces of fabric, corners can be created using one or more of these seam types. In the lower half of Figure 10, a sample corner is made with three different seam types. While any combination of the {IN, OUT, 180°} seams is possible in making a corner, in practice not all of these possibilities will lead to airtight structures. We constructed all of the possible corner types and tested them in a water bath to determine how well they held air, and the results are shown in Table II.

TABLE II POSSIBILITIES FOR AIRTIGHT CORNERS

Corner Style 1	Corner Style 2	Corner Style 3	Airtight
OUT	OUT	OUT	Yes
IN	OUT	OUT	
IN	IN	OUT	
180	IN	OUT	
180	OUT	OUT	
180	180	OUT	
180	180	180	No
180	IN	IN	
180	180	IN	
IN	IN	IN	

According to the results, a pneumatic chamber must have at least one seam of type OUT to be airtight. If an OUT seam is not present, then there is an air leak from a tiny hole at the corner. The cause of holes is related to the fabric and TPU thicknesses. TPU laminated fabric is thicker than un-laminated fabric. This causes the fabric not to be bent perfectly at each corner, resulting in a small hole. The TPU film is not thick enough to cover these holes. It is unknown if much thicker layers of TPU film would be able to solve this issue. Figure 11 shows several examples of corners that are airtight. Two examples of chambers that can be created using folds, with corners, are shown in Figure 12.

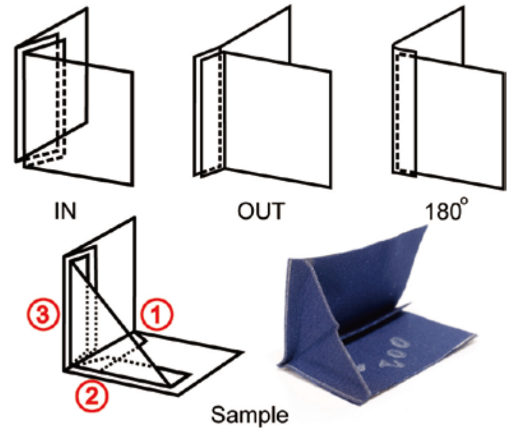

Fig. 10. Three types of possible corners for an airtight actuator.

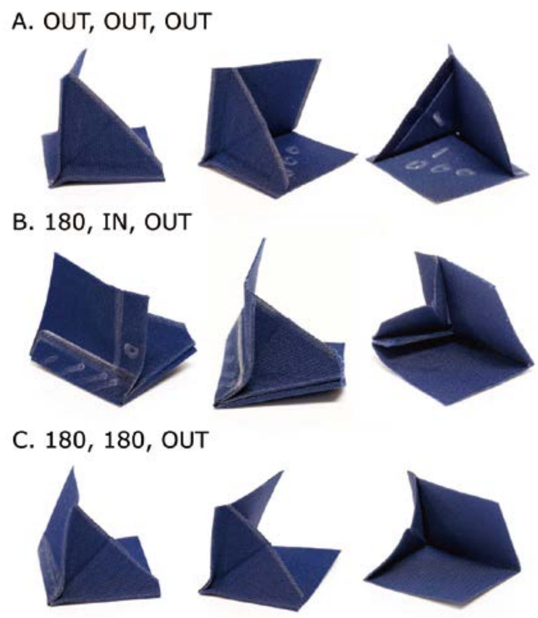

Fig. 11. Examples of airtight corners.

Fig. 12. Sample chambers incorporating folds and corners.

IV. Measurements

Tests were conducted to determine the maximum possible pressure able to be supported by a chamber made with this manufacturing process. Sample pneumatic chambers were fabricated and inflated until the pressure caused an air leak. According to the test, the available maximum pressure range was 310kPa to 330kPa, with average pressure of failure of 315kPa. Thus, soft robots and actuators made with this process should be designed to use pressures lower than 310kPa. In analyzing how the test chambers failed, it was determined that the TPU film tore off the fabric at a few small spots on the edges. This caused a small air leak under the maximum pressure, even though the chamber does not pop suddenly.

Tests were also conducted to determine what materials bond effectively with the TPU film. This is necessary to understand in order to build hybrid soft-rigid robots. Samples were constructed whereby two materials were bonded together at one edge, and then the un-bonded edges were placed in an Instron machine. The samples were pulled apart slowly until failure occurred, and the force of failure was recorded. The results are shown in Table III. ABS plastic bonds strongly with TPU film, with a strength exceeding that of a fabric-fabric bond. PVC plastic and Polyurethane (PU) plastic also bond reasonably well, and could be useful for internal rigid structures where lower amounts of adhesion are required. Acetal plastic and Aluminum do not bond very well at all.

TABLE III BOND STRENGTH OF JOINTS

	Maximum Bond Strength (N/cm)
Fabric - Fabric	66
Fabric – ABS	> 66
Fabric - PVC	53
Fabric - PU	32
Fabric - Acetal	~ 0
Fabric - Aluminum	~ 0

V. Applications

A. Pneumatic Hybrid Soft/Rigid Robot Arm

To demonstrate the use of the manufacturing process in creating larger structures, two pneumatic robots were fabricated. The first is a robotic arm, shown in Figures 1 and 13. The arm has hybrid structure: two joints are composed each of three bellows structures, enabling the robot to bend in any direction. In between, there are two inflated segments that act as structural elements. These are constructed with two sheets of coated textile, bonded at intervals so as to make long chambers along the length of the segments, then wrapped into a tube. These chambers are all inter-connected, so a single air hose can inflate them. At the end of each of the soft segments, a connection piece is formed from 3D printed ABS plastic. These connecting pieces integrate tube fittings directly, making an easy connection to the pneumatic chambers. Four tubes pass through the first bending segment and straight segment to provide air to the distal bending segment and straight segment. The robot can collapse if deflated, and each of the bending segments can bend to an angle of 180 degrees.

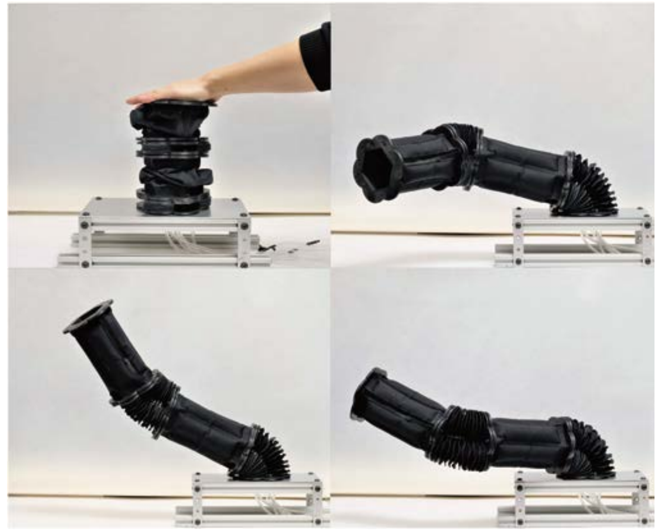

Fig. 13. The low-cost pneumatic soft/rigid hybrid robot.

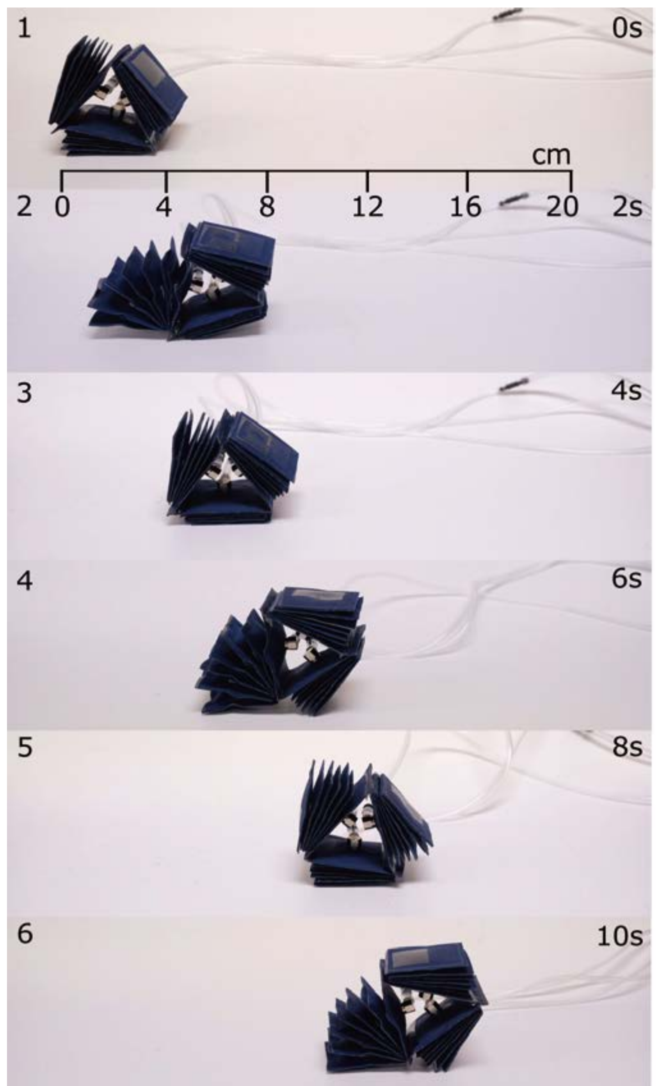

Fig. 14. Motion principle of the revolving robot.

B. A Revolving Robot

We also present a novel pneumatic robot that can roll itself along the ground (Figure 14). It is constructed entirely of fabric and TPU film, with the exception of tube fittings and pneumatic tubing supplying air. It is composed of three different bellows chambers arranged in a triangle. Each sub-chamber inside the bellows is glue asymmetrically to its neighbor, with the hole connecting them off-center. This causes the bellows to curl to one side when inflated. By positioning three of these in a triangle, and inflating them sequentially, the structure can be made to roll along the ground. Using any of the proposed manufacturing processes, this structure can be manufactured in 30 minutes after the materials are prepared.

VI. Conclusion

In this paper we present a novel manufacturing process for creating soft robots and hybrid rigid-soft robots. Two methods for layering materials and two methods for bonding them were presented, along with methods for including corners and rigid elements. The manufacturing process is simple and fast, requiring only a low-cost fabric (<$10 USD/yard) and a thermal adhesive film ($10 USD/yard). The ability to build robots quickly and cheaply makes these robots accessible to home hobbyists as well as researchers. The process itself can generate robots of a wide range of shapes and sizes, and the ability to embed rigid structures opens up many possibilities for off-the-shelf sensors and other circuits. More work still must be done to understand the limitations of this process, including the cycle life at various bend radii before tears appear in the pneumatic chambers. Additionally, much work can be done in determining the best sequences of folds that will lead to a desired shape.

Acknowledgment

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