A Layered Fabric 3D Printer for Soft Interactive Objects

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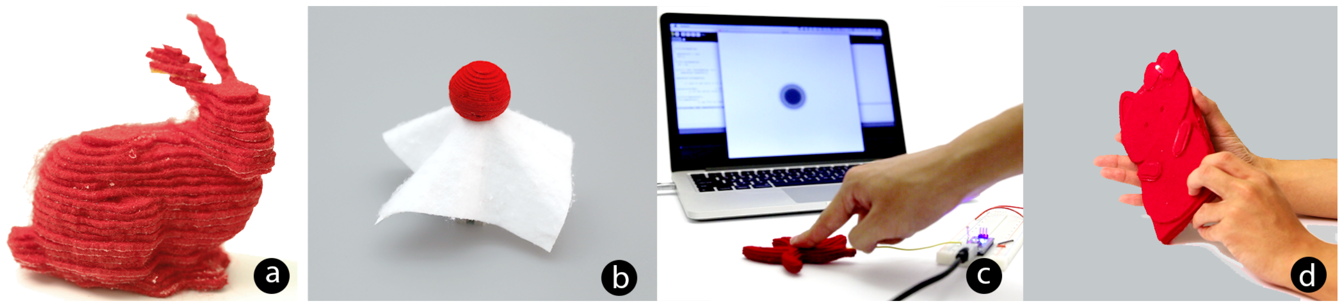

Figure 1. 3D printed objects from our layered fabric 3D printer: (a) printed fabric Stanford bunny, (b) printed Japanese sunny doll with two materials, (c) printed touch sensor, (d) printed cellphone case with an embedded conductive fabric coil for wireless power reception.

ABSTRACT

We present a new type of 3D printer that can form precise, but soft and deformable 3D objects from layers of off-the-shelf fabric. Our printer employs an approach where a sheet of fabric forms each layer of a 3D object. The printer cuts this sheet along the 2D contour of the layer using a laser cutter and then bonds it to previously printed layers using a heat sensitive adhesive. Surrounding fabric in each layer is temporarily retained to provide a removable support structure for layers printed above it. This process is repeated to build up a 3D object layer by layer. Our printer is capable of automatically feeding two separate fabric types into a single print. This allows specially cut layers of conductive fabric to be embedded in our soft prints. Using this capability we demonstrate 3D models with touch sensing capability built into a soft print in one complete printing process, and a simple LED display making use of a conductive fabric coil for wireless power reception.

Author Keywords

3D printing; laser cutting; soft materials; computational crafts; rapid prototyping; interactive devices

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

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INTRODUCTION

We are witnessing a boom in the arena of custom manufacturing technologies, from custom jeans (*e.g.*, `www.makeyourownjeans.com`) to websites that will print and mail a 3D model on demand (*e.g.*, `www.shapeways.com`).

At the same time, consumers increasingly prefer high quality and beautiful bespoke objects, as evidenced by the success of websites such as Etsy (`www.etsy.com`). However, these websites typically require individual craftspeople to produce such objects by hand. New additive manufacturing technologies (more commonly known as *3D printing*) provide an opportunity to manufacture highly custom objects on demand. However, the materials widely available for 3D printing and the range of functions supported by automated techniques are generally limited to plastic and metal. (Notable exceptions being printers using materials similar to silicon rubber such as [29], and the printer described in [10] which deposits layers of needle felted yarn).

Simultaneously, the use of electronics to create interactive physical objects from materials of daily life is becoming not only a research area (*e.g.*, [2, 3, 9, 20]) but also a commercial success (*e.g.,* `www.makeymakey.com`). Advances in toolkits for the construction of physical interfaces have made it easier to add circuitry, sensors, and actuators to physical objects (*e.g.,* [7, 8, 11, 13, 19, 25]). However, in these tools, the actual task of construction still may require special skills like sewing and soldering. In addition, as with bespoke objects, each new physical interactive system must be hand crafted.

Bringing these two threads together, our contribution is a printer that fabricates *soft objects* and provides *support for interactivity* including touch sensing and wireless power. Our printer can create objects with complex 3D geometry (Figure 1a), unique effects such as draping (Figure 1b), variable

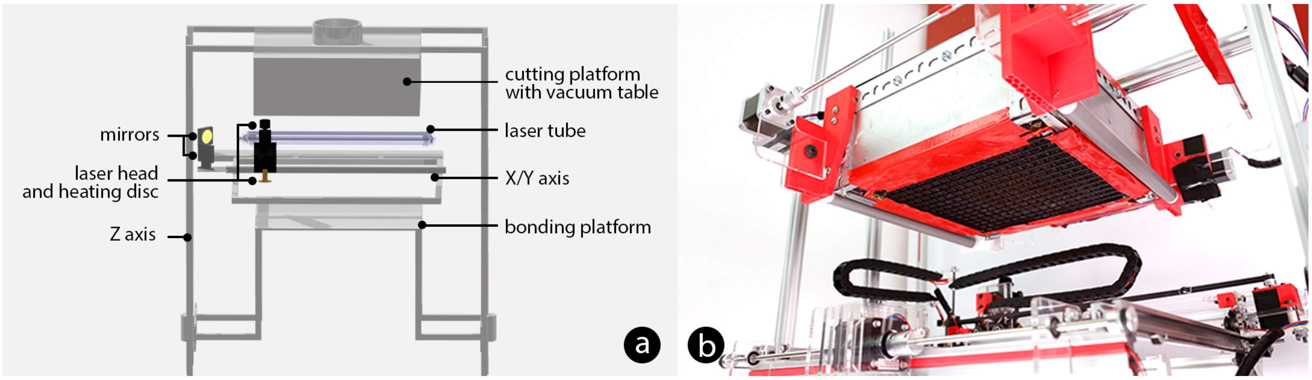

Figure 2. Layered fabric 3D printer: printer structure with cutting platform on top, bonding platform on bottom and laser head and heating disc moving in the XY plane.

flexibility (Figure 10), support for capacitive touch sensing (Figure 1c), and even coils made of conductive fabric which can be used for wireless power transmission (Figure 1d). We believe our printer opens new opportunities in forming interactive and functional 3D printed objects which are flexible and soft to the touch. This in turn adds a new tool to the HCI toolbox which expands our capacity to build interactive objects that reach the user in new (and more familiar) ways.

Our approach is conceptually related to other layered printing technologies involving paper [15] and metal [5]. Our printer cuts the contour for each layer from a roll of fabric and bonds it to layers of a 3D object already formed below it. Our printer cuts this 2D contour from a flat section of fabric using a high-powered laser and bonds it to the previous layer using a fusible heat sensitive adhesive sheet of a type already widely used in consumer sewing.

Mechanically, our printer is structured similarly to other 3D printers in which the print head can easily be moved within a Cartesian system (along the X, and Y axes of the print area). Unlike past printers, ours uses two separate working platforms, one for cutting, and one for bonding. The bonding platform, on which the 3D form is fabricated, is at the bottom (and moves along the Z axis). The cutting platform is located upside down above this, directly below a vacuum table which secures the fabric in place while it is being cut (Figure 2).

Our device supports printing with two separate types of off-the-shelf cloth (such as felt and conductive fabric) within an object. By manipulating fabric types and/or interior geometry we are able to add functionality to 3D printed cloth objects.

We next describe our primary contribution, the design of a novel soft object printer. Following that, we demonstrate the basic application of the printer to printing soft objects, manipulating the deformability of those objects, and printing in multiple materials. Having introduced the basic construction and functionality of our 3D printer, we go on to show how it can be used to construct interactive objects that can sense and react to the user through the use of conductive fabric. We end with a discussion of limitations of our current printer and possible future improvements.

3D FABRIC PRINTER DESIGN

Fabric is a material that by definition is manufactured from raw materials into sheets that are normally intended to be cut and bonded into new forms (most typically by sewing). Fabric is usually sold in rolls, and is available in a wide variety of colors, patterns, textures and thicknesses. Fabric can therefore potentially be used to form 3D objects with unique features and rich tactile qualities.

However, fabric is not suitable for traditional additive 3D printing technologies like fused deposition modelling (FDM), stereo lithography (SLA), or selective laser sintering (SLS); which use homogeneous materials (plastic filament, liquid, and powder, respectively) that can be deposited only at selected locations within a print.

An alternative more suited to fabric is layered fabrication [6, 32], which builds objects from sheets of material, cutting each sheet to shape and bonding it to the print in progress. While layered fabrication printers exist for paper [15] and metal [5], fabric presents a unique set of handling and cutting challenges that we address in our design.

Specifically, tool-based cutting (used in metal and paper printers) is likely to snag and deform fabric layers, and laser-based cutting – while snag-free – requires layers to be cut on a separate bed and moved to the print in progress, potentially requiring a complex transfer system. Our design (Figure 2) solves this problem by using an inverted cutting bed, which allows our printer to laser cut fabric while avoiding complex fabric handling schemes.

The rest of the printer design (Figure 2) follows from this notion of an inverted cutting bed. The cutting bed is fixed in place at the top of the printer. Fabric is fed to the bottom face of the bed by rollers mounted to the sides, and held in place by a vacuum during cutting. Cutting is performed by a laser directed through a print head which can move freely in X and Y below the cutting bed. The print head also carries a downward-facing heated metal disc, which is used to bond layers together. The final print is assembled on a bonding platform, which generally remains below the print head, but can raise and lower in Z in order to facilitate cutting and bonding operations.

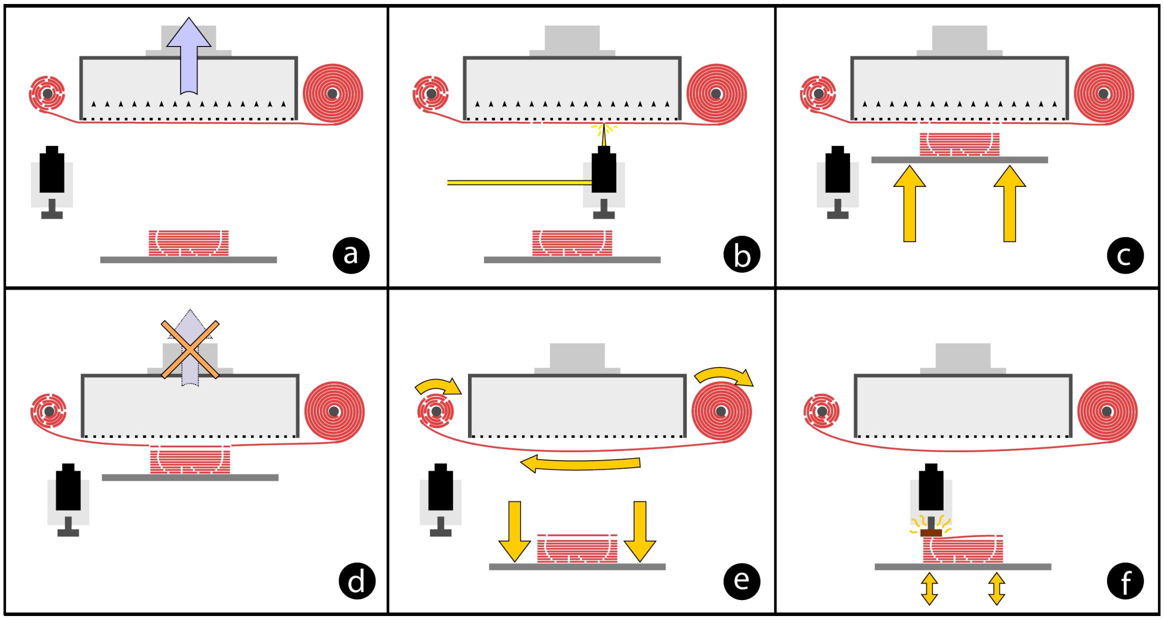

Figure 3. Adding a layer to a print. (a) the vacuum holds the fabric to the cutting table; (b) the layer shape and bounding box are laser cut; (c) the bonding platform is raised; (d) the vacuum is turned off and the freshly cut layer remains on the stack; (e) the bonding platform is lowered and the fabric is advanced; (f) the new layer is bonded to the existing layers with the heating disc.

Before describing these systems in detail, we first discuss the printing process. Before printing, fabric prepared with fusible adhesive (Figure 5a) is rolled and loaded onto the machine, the bonding platform is covered in a layer of fabric, and the heating disc is brought up to temperature. Then the print process proceeds as follows (illustrated in Figure 3):

	Printing Routine
a	Turn on vacuum to hold fabric to cutting table
b	Cut 2D layer shape(s) and bounding box in fabric
c	Raise bonding platform to touch cut fabric
d	Release cut fabric by turning vacuum off
e	Lower bonding platform and advance fabric
f	Heat bond new layer to print

Once the 3D model is fully printed, the result is a rectangular prism made up of layers of fabric. The outside support material must be manually peeled off if the inside model has a complex shape, or simply cut off with scissors if the inside model is straightforward. This post process step is analogous to the remove of support material in a traditional 3D printing process.

The build volume for our current prototype is 10 x 10 x 10 inches (254mm^3). However, printers of larger sizes could be easily constructed using this same design. The primary physical structure of the printer is constructed with off-the-shelf aluminum extrusion. Following the design of a number of current consumer 3D printers, motion is actuated with stepper motors and timing belts for the X and Y axes, and with a paired set of stepper motors and lead screws for the Z axis.

The printed object slowly stacks up on the bonding platform during this process. However, the cutting platform for our printer is located at the top of the printer. To hold the fabric flat, the printer makes use of a 12 x 12 (305mm^2) inch vacuum table, visible on the right side of Figure 2, largely enough to cover the build volume, and to hold the fabric at the top of the printer. The vacuum table consists of a thin metal grid and a small closed chamber with a 2 inch (50mm) air pipe on top. The vacuum is provided by a conventional shop vacuum and hose which also serves to remove smoke and fumes during laser cutting.

The fabric is stored on rollers mounted at the four sides of the printer (supply and take-up rolls for each type of fabric that is loaded). Stepper motors move the fabric, rolling up the section that was just cut on the take-up side and unrolling fresh fabric off the supply side so that a flat section of fabric is located in the cutting area (just below and suctioned to the vacuum table). Note that we pre-process our rolls of fabric by cutting them into 10” wide strips and attaching a heat sensitive adhesive sheeting to the bottom surface of the fabric.

The most complex parts of the print algorithm are layer cutting and layer bonding. Cutting is performed with a laser. For a single layer the profile shape(s) forming the layer are cut, and then a surrounding rectangle, which forms support material for possibly overhanging layers later is cut around this. Bonding is performed with the heating disc. After each layer is bonded, the roller supplying fabric to be used in the next cut moves a new segment of fabric into place for cutting. Both cutting and bonding are described in more depth in the next two subsections.

Layer Cutting with a Laser

To cut 2D shapes for each layer out of a segment of fabric, we employ a laser beam generated from a water cooled 40 Watt CO_2 laser tube of the type commonly used in commercial

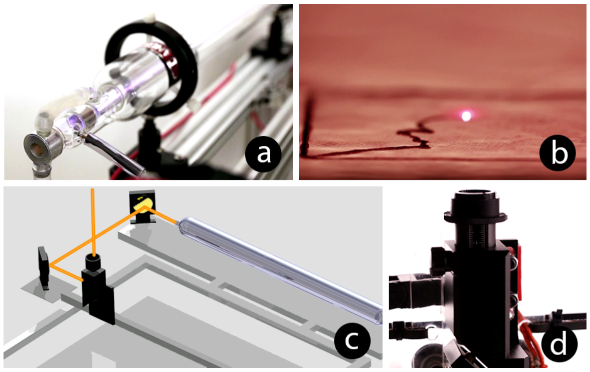

Figure 4. Layer cutting. (a) laser in action, (b) cutting fabric, (c) laser beam path, (d) laser head containing mirror and lens.

laser cutters (Figure 4a). The laser tube generates a high power infrared laser beam which, when focused to a small spot, vaporizes material leaving a clean cut edge (Figure 4b).

The laser beam is used to cut a 2D layer from the fabric, which is located on the fixed cutting platform vacuum table at the top plane of the printer. Thus, the laser beam needs to be capable of cutting at any (X, Y) position, but does not need to be adjusted in the Z axis. To facilitate this, the laser tube is arranged at the back right of the 3D printer along the bottom plane. As shown in Figure 4c, the beam travels along the back of the printer in the X direction by a fixed amount. A moveable mirror then controls the distance it travels first in the Y direction (along the left side of the printer) and next in the X direction (inwards into the printing area). Finally the beam travels through the laser head (shown in Figure 4d), which contains another mirror and a focusing lens, and finally up by a fixed amount in the Z direction to the fabric. Direction changes in the beam are accomplished using silicon coated gold reflective mirrors (two of which are visible as small squares in Figure 4c).

Note that the second mirror and the laser head are attached to a movable gantry which moves in the Y direction. In addition the laser head can move in the X direction. Together, these movements can cover the entire XY cutting plane. Laser intensity is relatively unaffected when the laser head moves, ensuring a continuous cutting beam without the need to move the large laser tube.

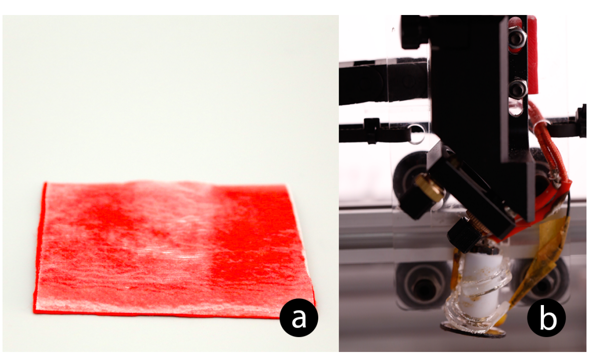

Figure 5. Bonding. (a) fabric with fusible adhesive, (b) heating disc with heating cartridge and temperature sensor.

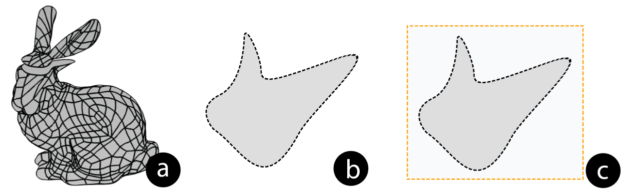

Figure 6. Cutting strategy. (a) 3D model, (b) extracted slice, (c) cutting route. The black inner contour is cut once at low power, while the orange outer contour is cut multiple times at high power to ensure clean separation from the feed fabric.

Layer Bonding with a Movable Iron

Once cut, the fabric for a layer is bonded to the previous layers. The adhesive material we use bonds with fabric when heated and pressed together. It is commonly used as a non-stitched solution to bond layers of fabric in the handcraft sewing community using an iron to provide heat and pressure. We chose fusible adhesive as the layer bonding solution due its very rapid curing time and the simplicity of the bonding mechanism (Figure 5a). We currently attach the adhesive to the fabric feed stock in a manual process before printing starts, but this could be automated in future devices. The fusible adhesive we chose is Heat-n-Bond™ (`www.thermowebonline.com`) for its convenient paper backed configuration, but we also tried several other fusible adhesives and obtained similar results.

To apply bonding heat and (slight) pressure our printer makes use of a 20mm *heating disc* (Figure 5b). This heating disc was constructed from an off-the-shelf soldering disc (`www.masterappliance.com/content/35404-tip-disc-round`. This is the smallest soldering disc we could find at the time) with a small heating cartridge (`www.makergeeks.com/cecahefor3dp.html`) and temperature sensor (thermistor) inserted. The disc is heated to 200°C and held there using a PID temperature controller. Once one layer is printed and placed on the previous layer stack, the heating disc is moved in and pressed onto the cut out pieces to bond the two layers. In our tests with 2mm acrylic felt, we found that 7 seconds ensures a strong bond.

Cutting and Bonding Algorithms

The previous two sections introduced the hardware structure of our printer. This section provides details on the software side of fabric printing. The basic approach used in our printer software involves slicing a 3D model as with conventional 3D printers. The model is sliced into 2D contours with a height corresponding to the height of the fabric being used. To ensure that contours stay in the correct position no matter how small, and to enable overhang geometry, our printing uses the fabric that is not part of the final model as support. A rectangle of support just larger than the bounding box of the object being printed is cut from the fabric at each layer (Figure 6).

To further ensure the stability of potentially small blobs that are part of the 2D contour, we set the laser to cut almost but not entirely through the fabric during the contour cut. This leaves a few points with weak connection to the support rectangle, ensures that even if the 2D contour shape is smaller

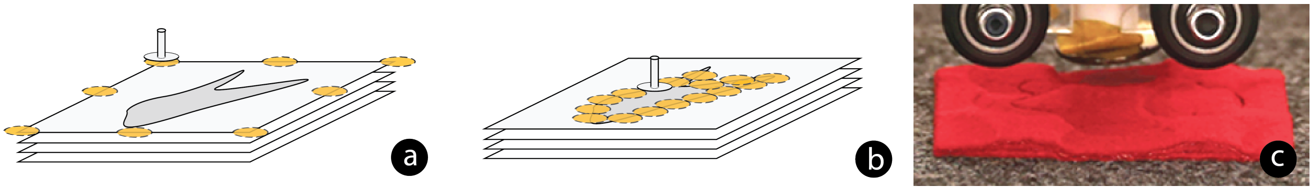

Figure 7. Bonding strategy. (a) bonding at side and corners, (b) bonding along the contour, (c) bonding in action.

than the grid size of the vacuum table it will not fall prematurely or be sucked into the vacuum table before the bonding platform arrives. These cuts are easy to 'finish' during the manual support removal process simply by tearing away the support material.

The bounding rectangle is cut with high power at least two times to ensure that it completely separates from the original fabric sheet and is easily released onto the bonding platform when it arrives.

Once the bonding platform has retrieved the new layer and lowered back to its base position, bonding can begin. The heating disc is typically not big enough to iron the entire rectangle at once. Thus, we designed a stamping route plan for bonding (Figure 7). Each 'stamp' in the route is performed by moving the print head to the given location, raising the bonding platform so that the top layer of the print is firmly in contact with the heating disc, waiting a set amount of time, and then lowering the bonding platform again.

The stamping route begins with the the four corners and four center points of each side of the cutout support rectangle. This ensures a stable bond at the outer edges. Only eight points are stamped so that support removal will be easier (Figure 7a). Next, the heating disc stamps along the contour path with the diameter of the disc as the step distance. This ensures that the whole contour will be fully stamped and bonded to the previous layer (Figure 7b). If the entire contour area is smaller than the disc area, it is stamped only once. Figure 6c shows the bonding head in action.

The shallow dent in Figure 7c is caused by the heating disc pressing into the material. We found that the dent did not deform the overall shape of the printed object, although it might be visible in a model with a very large, flat top layer. In the future, such dents could be reduced with a higher temperature heating disc, with shorter stamping time, or with a steaming iron that can transmit heat to the fusible adhesive more efficiently.

The control software used is Repetier-Host v0.95 (`www.repetier.com`) with no modification and the 3D model slicer is Slic3r v1.1.7 (`www.slic3r.org`, also unmodified). The printer is controlled with an Arduino Mega 2560 microcontroller driving a RAMPS1.4 printer control board (`www.reprap.org/wiki/RAMPS_1.4`) with Repetier firmware (`www.repetier.com`). The only modification we made to the firmware is to support generation of a pulse width modulated (PWM) signal for laser beam intensity control. GCode generated from the unmodified Slic3r program is processed by a custom GCode rewriting script to generate cutting path, vacuum machine control, stamping and bonding platform moving code. This modified GCode is then sent to the printer using the Repetier-Host program.

PRINTING SOFT OBJECTS

In this section we showcase the basic printing capabilities of our 3D fabric printer in forming soft objects, including complex soft geometries with sharp edges and overhang structures, soft objects with different stiffness in different areas, and soft objects with a draping effect printed with two different types of fabric.

The Stanford bunny model (Figure 8a) is printed with standard printing routine introduced above. It consists of 32 layers of acrylic felt fabric resulting in a 64mm high final product. Despite the relatively thick 2mm felt used in the print, it preserved most of the details in the underlying 3D digital model like the nose and ears. Also notice the relatively complex overhanging shape in the ears of the bunny. Because of the cutting strategy we used, fabric from the bounding box area of the previous layer serves as support for overhangs, including very small and sharply overhung features such as these. Figure 8b shows the completed printed object enclosed within its support. The very top layer of the fabric is not flat because of the stamping of the heating disc, but the finished result is not influenced by the uneven surface. Figure 8c shows the support partially removed and the bunny emerging from the printed cube. The printed object is true to the under-

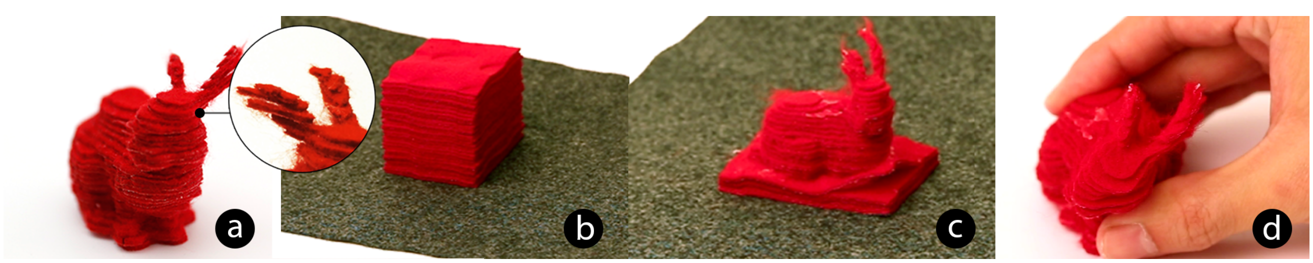

Figure 8. Printed soft Stanford bunny. (a) Stanford bunny, (b) finished cube, (c) removing support, (d) deforming the model.

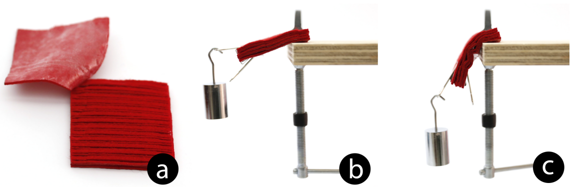

Figure 9. Deformation manipulation. This square has many parallel cuts in its internal layers (a). It is stiff when bent perpendicular to the cuts (b), and quite flexible when bent parallel to them (c).

lying model, yet soft and deformable as is shown in Figure 8d.

Note that because of the bonding method we employed, as well as the relatively thick and compressible fabric used in our examples, the area being pressed can become slightly condensed and in some cases slightly stiffer than the untouched areas. This could be avoided by using an improved bonding mechanism, an area of future work we cover in the discussion section.

Resolution along the Z axis (*layer height*) is limited by the material thickness. In our examples the layers are apparent because the layer thickness to overall height ratio is high. This, however, does not imply our printer has a low precision design. In fact, our printer shares similar positioning mechanisms as other consumer grade 3D printers and laser cutters. Although we did not run a full measurement on this, we expect that our printer can achieve resolutions in the range of 50 microns, similar to consumer 3D printers with similar motion platform design. Also, if a thinner material were used, the layers would become less noticeable. Printing time, however becomes longer when thinner layers are used.

The printing time for our Stanford bunny example is two and a half hours (operated with double cutting of outer support rectangles and a five second bonding stamp time). Printing time varies based on the model size, height and the length of the layer contours. By a rough estimation, our printer's bonding speed is 10 to 13 sec per 20mm, and the time for raising or lowering of the bonding platform is 62s per travel on average. Thus unlike conventional printers where printing and filling the model are the most time consuming parts, with our printer, movement of the bonding platform, along with the bonding steps take most of the time.

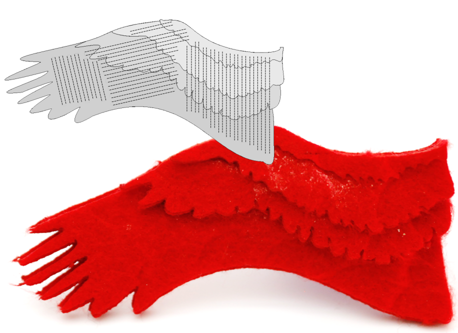

Figure 10. Deformation manipulation. This wing was printed with internal slots that change how it bends.

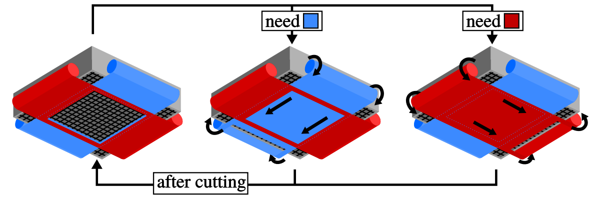

Figure 11. Dual material printing. (View of the cutting bed from below). Only the material for the next layer is advanced, leaving a 'window' in the unused material.

Deformation Manipulation

By embedding appropriate patterns of cuts inside a solid print we can manipulate the bending and deformation properties of different areas within one printed 3D soft object. To accomplish this, we can use very small cuts (removing gaps of material twice the narrow kerf width of the laser cut) placed inside an otherwise solid 3D print, but leaving the surface of the model intact. As is shown in Figure 9, a row of parallel cuts will substantially reduce the stiffness of that section of the print in one bend direction, but much less so in the orthogonal direction. With this approach we can manipulate bending direction and stiffness of different areas in one printed process without manual intervention. Figure 10 showcases a wing example where the apex and the root of the wing are easier to bend vertically while the middle part of the wing is more bendable horizontally by making use of inner cut patterns in different directions. This manipulation is hidden in the interior and does not affect the outside of the object.

Dual Material Printing

With the ability to feed two separate types of fabric into different layers of one print, we can produce 3D objects with additional variations. Here we will first introduce how the two layer printing works and follow this with a simple printed example.

Separate layers of material can be loaded onto the cutting bed from one roll feeding left-to-right and another feeding front-to-back (with slightly offset vertical positions so that they will not affect each other as they are being loaded but can both be pulled to the vacuum bed). Before printing, a 'window' the size of the support bounding box is cut in both materials. Then, during printing, only the material to be used in the next layer is advanced. When the layer moves to the stack, its bounding cut becomes a window in the material, and the process can be repeated. This process is illustrated in Figure 11.

In Figure 12 we show two objects created with dual fabric printing. The first is a toy clothes example printed with cotton fabric and fleece (different from the felt used in other

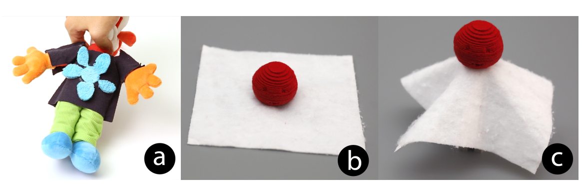

Figure 12. Dual material examples. (a) a toy doll t-shirt printed with cotton and fleece, (b & c) printed object with a draping effect.

examples). In this example only the center of the flower is bonded to the clothes, creating a decoration with an organic shape. The second example is a traditional Japanese sunny doll (named *teru teru bozu*) used to pray for good weather. The doll is usually made with paper or cloth with a round top as the head and draping cloth as the body. In this example we printed the head in red felt and the body in white felt. Though printed as a flat square, the white felt body drapes – like the cloth it is – to form a body. This would be hard to acheive for a printer that did not use cloth as its material.

PRINTING ELECTRICALLY FUNCTIONAL OBJECTS

As stated in the introduction, our goal in doing this research was not only to use novel materials to create 3D printed objects, but to enable manufacturing of the next generation of *interactive* devices using such materials. This requires the introduction of electrically conductive material and possibly electronic components into soft objects, in a fashion that preferably requires little manual intervention.

In this section we consider how such electrically functional, but still soft and flexible, objects can be created with our printer. The key to our method is to embed profiles cut from off-the-shelf conductive fabric sheets into printed objects as a functional layer. With one roll loaded with normal non-conductive fabric and the other loaded with conductive fabric, we can print electrically functional 3D objects with no or minimal human intervention.

Printing Touch Sensors

By utilizing a conductive fabric as one of our material feeds, we can make custom printed capacitive touch sensors as a part of a normal print. Figure 13a showcases a necklace pendent in the form of a soft starfish with an embedded capacitive touch sensor (connected to an external microcontroller such as an Arduino). Figure 13b is a printed capacitive sensor configured as a slider, connected to an off-the-shelf teensy microcontroller (**`www.pjrc.com/store/teensy31.html`**). After connecting it with only two wires, the soft printed pad is ready to serve as a physical slider for interaction. One can imagine a more complicated 3D printed soft toy with muliple touch sensitive areas.

Printing Circuit Paths and Vias

Since we can place arbitrarily cut shapes within a layer, we can also use conductive fabric to create the ‘wiring’ between

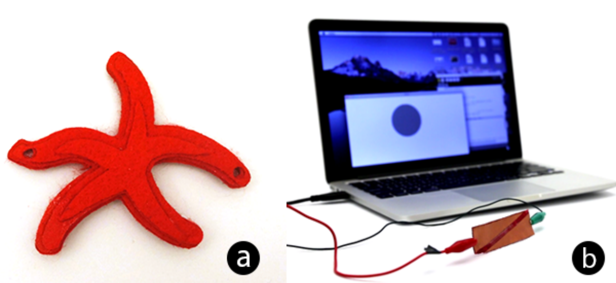

Figure 13. Printing capacitive sensors. (a) starfish touch sensor, (b) touch slider.

electronic components — the rough equivalent of printed circuit boards, but made entirely from, and embedded inside of, soft fabric. Because our printer leaves both the conductive material that makes up the paths and the conductive material outside them in place, we need to take care that this does not create shorts in the circuit. One approach to ensure this is to pause the print and manually remove segments of this extra conductive material.

It would also be possible to cut conductive traces in a purely automatic fashion without the need to pause the print. We can do this by increasing the kerf of the laser cut to create a sufficient gap between the intended conductive trace and the material around it. This approach is similar to what was done in the wing to remove inner material automatically so that it would bend more easily. Such small amounts of inner material can be removed by increasing laser power, slowing down movement of the cutting beam and/or cutting the path multiple times with a small offset. However, we feel that more testing is needed to determine how much gap is required in order to ensure robust long term functioning of traces constructed in this fashion, especially when objects are subjected to substantial bending or other deformations over time. For example, it may be that additional bonding time is needed along the gaps between traces to avoid short circuits from forming.

To allow ‘circuit boards’ whose traces cross, and to allow wiring to be routed throughout a 3D form, it is also important to be able to create connected circuit paths which go beyond a single horizontal layer. As in conventional printed circuit boards we can do this by connecting otherwise separate layers at a single point — a *via* connection between the layers

To construct a via connection we place a non-conductive fabric layer between two conductive fabric layers containing the circuit traces we wish to join. As illustrated in Figure 14a we place a hole in the insulation layer at the point of the via (which must be manually removed during the print). We then press our heating disc down slightly further than normal in order to bond the top and bottom conductive layers through that hole. In experimenting with this technique we found that the adhesive we used for other parts of the printing was not suitable for via bonding because it formed an insulating layer between the conductive sheets it was bonding. We were however, able to use a different fusable *mesh* adhesive (**`www.dritz.com/quilting-sewing-supplies/sewing/glues-bonding-stabilizers/stitch-witchery-fusible-bonding-web/`**). This form of adhesive, while still heat activated, is porous and allows fabric from the top and bottom conductive layers to be pressed into contact through those pores while still bonding the layers firmly together. Another important limitation of this technique for constructing printed vias is that the via hole must be comparatively large — large enough to allow the heating disc to push material through it and reliably bond on the other side. In all our examples, we used a via hole slightly larger than the 20mm diameter of the heating disc. Smaller vias could be accommodated in future printers by providing an alternate, much smaller, heating element for bonding vias.

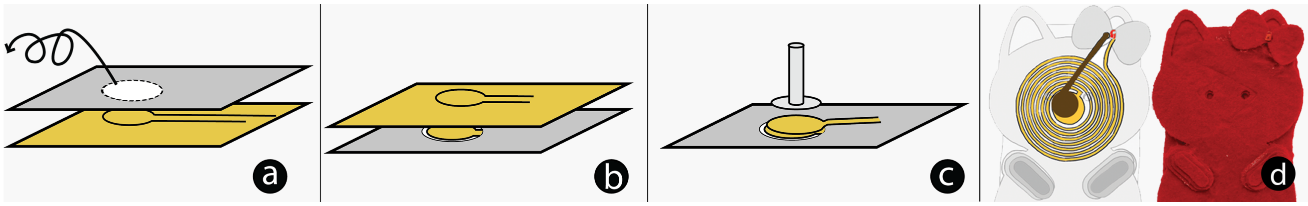

Figure 14. Printing a multi-layer circuit. (a) via hole on insulation layer, (b) top conductive layer, (c) press to bond top and bottom conductive layer, (d) conductive coil embedded in cellphone case design.

Figures 14d and 1d showcase an embedded circuit example with a printed via. Here we designed a smartphone case with an LED that can be wirelessly powered with energy harvested from the near-field communication (*NFC*) hardware built into the phone. To achieve this, two layers of circuit are embedded in the phone case. The bottom layer consists of eight loops of conductive fabric coil serving as an inductor to receive energy from the coils of the NFC hardware in the phone. The second conductive layer is a circuit trace from the center of the coil to the top right corner of the phone case to complete the circuit loop. The two layers of circuit are connected in the center using the via approach introduced above. A set of fabric through hole pads the size of an LED is designed into the model so that after the phone case is printed, one just needs to plug in an LED through the holes to complete the circuit.

RELATED WORK

The work introduced here builds on personal fabrication and soft material printing. Personal fabrication is a recently emerging research area. Different approaches have been explored in printing functional actuators and sensors (including interactive light pipes and speakers) with commercial 3D printers [33, 12]. Researchers have also fabricated mechanical functional objects such as 3D printed balancing and spinning objects [1, 22]. Interactive fabrication has also been examined with pen annotations in 3D [28], interactive laser cutting [17], and interactive handheld cutting and spray painting [35, 26].

Research has also examined the design process associated with 3D printing. Because printing can be very slow, significant effort has been put into supporting iterative design through rapid prototyping. Recent work in this domain has including printing objects that can be quickly assembled from a mix of Lego® and 3D printed parts [18] and printing 3D objects using a wireframe structure instead of a solid structure [16].

With respect to printing materials, soft objects have been printed with needle felted yarn [10]. In contrast to our approach, [10] only supports a single material and produces less physically robust results. There are also printers which produce soft prints using materials such as a UV cured silicone rubber-like material [29], and specially formulated thermoplastic elastomer filaments [4, 14]. These materials all lack the variety of textures of fabric and thus cannot be as easily customized to the preferences of users.

We have also seen a wide increase in the range of objects being enhanced with sensors and actuators including for example plush toys [30], fabric [9], knitting [23], and objects such as a candy dispensers and picture frames [31]. Most objects that we wear or otherwise hold close are best made from soft materials such as cloth, and thus we are particularly interested in work being done to advance the interactivity of soft materials. Much of this work comes from advances in soft robotics [21], which has driven the development of flexible soft sensors [34, 27]. Other advances have involved the use of conductive fibers (*e.g.*, [20, 3]) and soft circuits (*e.g.,* [2]).

While advances in what can be constructed are critical, widespread use of these technologies requires efforts that make construction easier for end users, support repeat manufacture of the same device and so on. For example, Phidgets [8] lowered the floor for end users to make use of sensors and actuators, while tools like Midas [25] and Sauron [24] provide support for the design and fabrication of touch sensors which can be applied to 3D objects (but not for soft materials). While many toolkits that support the construction of physical interfaces in various ways have been created [8, 11, 7, 13, 19, 25], they do not remove the need for special skills like sewing and soldering. In addition, as with bespoke objects, in most cases each new physical object must be hand crafted. Our work builds on this past work by supporting the automatic creation of 3D objects with embedded interactivity.

DISCUSSION

We now discuss lessons learned when designing our printer including limitations and possibilities for future improvements.

Bonding Method

The bonding method for our current printer design is to use heat sensitive adhesive with a heating disc. To ensure a solid bond, each press of the heating disc lasts several seconds. This leaves a shallow dent at the pressed area and makes a printed surface with slightly heterogeneous stiffness. One way to improve this is to implement a steaming head in combination with the heating disc. Steam delivers heat more easily through fabric and may, therefore, reduce pressing time and press strength. Another improvement that could be made is to upgrade the heating disc to a small heating roller so that instead of stamping at discrete points, the roller head might press and heat the contour in a more continuous manner along its path. This may further eliminate uneven surfaces and make the edge stiffness of the object more evenly distributed.

Printing Time

Printing time in our current printer design is relatively slow and is limited first by our bonding method, which currently requires each bonding location to be pressed for several seconds, and next by the movement of the bonding platform up and down, which takes roughly one minute per one-way travel. Bonding time might be improved using one or more of the techniques described above, or by using a large area heating element to bond the entire layer at once. However, for this second approach it is likely that modifications to surrounding support material may be required in order to both make it removable and ensure that it does not firmly bond where it is not desired. In addition, it should be possible to substantially increase the vertical speed of the bonding platform using larger motors and a drive train that is geared more aggressively.

CONCLUSION

In this paper we have presented a new type of layer-based 3D fabric printer that can form precise, yet soft and deformable 3D objects from rolls of off-the-shelf fabric. Our printer cuts fabric in the profile of layer slices with a high powered laser and bonds those shapes to previously cut layers using a heat activated fusible adhesive. In this way, objects are built up layer after layer to form whatever 3D geometry has been specified. Material outside layer profiles is temporarily left in place to provide support for overhang features in the layers above it (but removed at the end of the print to reveal the printed object). Our printer supports the use of two different fabric types in one print. This allows a number of additional features to be included in prints. For example, objects with printed 'wiring' can be constructed using conductive fabric. This 'wiring' is completely flexible since it is formed with, and entirely embedded inside of, fabric sheets. We have used this capability in several proof-of-concept demonstration objects including a soft cell phone case which contains a printed fabric coil capable of harvesting power from the NFC hardware of an off-the-shelf cell phone.

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