Printing Teddy Bears: A Technique for 3D Printing of Soft Interactive Objects

Scott E. Hudson
Human-Computer Interaction Institute, Carnegie Mellon University and Disney Research Pittsburgh
5000/4720 Forbes Ave., Pittsburgh, PA15213
scott.hudson@cs.cmu.edu

ABSTRACT
This paper considers the design, construction, and example use of a new type of 3D printer which fabricates three-dimensional objects from soft fibers (wool and wool blend yarn). This printer allows the substantial advantages of additive manufacturing techniques (including rapid turn-around prototyping of physical objects and support for high levels of customization and configuration) to be employed with a new class of material. This material is a form of loose felt formed when fibers from an incoming feed of yarn are entangled with the fibers in layers below it. The resulting objects recreate the geometric forms specified in the solid models which specify them, but are soft and flexible – somewhat reminiscent in character to hand knitted materials. This extends 3D printing from typically hard and precise forms into a new set of forms which embody a different aesthetic of soft and imprecise objects, and provides a new capability for researchers to explore the use of this class of materials in interactive devices.

Author Keywords
Additive manufacturing; soft materials; computational crafts; interactive devices.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
Additive manufacturing – most commonly referred to as 3D printing – offers exciting new possibilities for the creation of physical objects. It allows object geometry to be specified ("drawn") in purely virtual form on the computer, and then realized in physical form seemingly "at the push of a button". As a result, it enables both rapid prototyping of physical forms and new forms of mass customization not previously practical. Further, some of these systems offer the ability to create new forms which are difficult or impossible to manufacture in other ways, opening up new possibilities for *what* can be manufactured. Finally, recent advances have dramatically reduced the cost of this technology [7], making it accessible to a broad range of people and allowing the formation of a community of mostly non-professional makers who can share and customize object designs (see for example: http://thingiverse.com).

Figure 1. A 3D Printed Teddy Bear. Solid model (top left), printing in progress (top right) and result (bottom).

In this paper we introduce a technique which extends the range of additive manufacturing to include a new class of material which we believe is interesting to the Human-Computer Interaction (HCI) community. Currently, nearly all additive manufacturing has focused on the production of precise forms using hard materials such as plastic and metal. (A notable exception being printers capable of very precise manufacture of flexible materials similar to silicon rubber, such as the Objet Connex printer). In the work presented here we consider a technique to manufacture objects made from needle felted yarn (see Figure 1). These

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objects are soft and flexible – with a feel and form somewhat analogous to hand knitted or crocheted objects. This material moves away from an aesthetic of very precise shapes and hard lines, towards the more varied texture and feel of hand crafted fiber arts. However, at the same time we retain the ability to create designs using solid modeling software and fabricate them on demand, which is central to the advantages of additive manufacturing. This opens up new possibilities in the creation of interactive objects which are soft and flexible, and so more suitable to be worn or simply "held close". Figure 1, shows one such example in the form of a printed Teddy Bear.

In the next section we will very briefly consider related work. We will then consider the details of how our prototype printer is constructed and used. Then we will explore several techniques for going beyond creating of simple soft solid forms, considering how hard objects (such as electronics) might be embedded inside prints, how the connection between hard and soft materials can be managed, and how we might systematically manipulate the stiffness of objects. The design and construction of an example object using these techniques will be considered, then limitations and prospects for future will be discussed.

RELATED WORK

Substantial prior work has been done on embedding electronics in fabric and fabric-based objects (most notably clothing). This has in turn been an enabler for new types of interactive devices and new styles of interaction. We will not attempt to review this large literature here, but can point to several important themes and a few exemplars of each. These include: the development of techniques for creation of circuits (and more specifically for creating sensors) on and with fabric [2,10,3,5], examining new applications that are enabled by an ability to work with a soft, flexible, or otherwise more "personal" forms for electronic device [1, 12], and the personal and community effects engendered by extending electronic making into new domains, looking for example at the relationship of this work to crafts and the DIY movement [6,13,10].

More generally, new technologies for personal fabrication have begun to open up new possibilities for exploring the space of interactive devices. Recent work has looked at making use of new materials for 3D printed input and output components (see for example [18]), new fabrication techniques using existing technology (such as the innovative use of laser cutting in [9]), as well as new classes of fabrication (such as the hybrid manual/automated techniques introduced in [20]). Work has also considered better systems and tools for supporting existing fabrication processes for prototyping of devices (see e.g., [14,15]).

Another emerging area of considerable overlap with the work presented here is *soft robotics* (see recent surveys of this very large area in [11, 17]). While some of this work is motivated by a desire to more easily interact with people, much of this work is also concerned with the detailed mechanics of control and manipulation of soft bodies as well as the details of sensing in this domain. Soft sensors in particular are of considerable interest for HCI (see for example [16, 19]). These developments all form important prerequisites for progress in this area.

Figure 2. The felting needle used in this work is triangular with barbs in the form of notches placed approximately 2mm apart around the needle.

CONSTRUCTION OF A FELTING PRINTER

Felt is a textile which is created by entangling and compressing sheets of fibers (rather than weaving them). The printing technique introduced in this paper involves a process of *needle felting* where a barbed needle (see Figure 2) is repeatedly passed through a body of fibers in order to draw fibers down into layers below and entangle them there. Barbed needles are used for this purpose in the commercial manufacture of felt (which is normally done in a wet environment such as soapy water, which we do not use) as well as the craft of needle felting. Needle felting craft objects include fibrous decorative materials such as felt, yarn, and loose fiber *roving*, joined onto (i.e., entangled over and through) loosely woven or knitted clothing (such as a sweater). In a more closely related, but less structured form, needle felting can also used to construct full 3D forms from fiber (see for example: http://www.stephaniemetz.com/portfoliocurrent.html).

In the process introduced here we produce three-dimensional felted forms in a layered fashion. Like many other forms of 3D printing we form solid objects by creating a series of thin layers of material, each representing a horizontal slice of the final geometry. By working from the bottom of the object up, and bonding each layer of material together (in this case by needle felting) a complete 3D object with fairly arbitrary geometry can be formed. For each layer in this process we place fiber, in the form of yarn, along a winding 2D path which fills the layer. As we deposit this yarn along the printing path, we bond it to the layers below by repeatedly piercing it with a felting needle – dragging down individual fibers from the yarn into the layer(s) below and entangling them there.

To accomplish this process mechanically we use a new custom *felting print head* (described below; see Figure 3) attached to a precision 3D motion platform. The motion platform is driven by stepper motors and control electronics which respond to the same "G-Code" commands used for RepRap 3D printers [7] and very similar to those used by many CNC machines [8]. Specifically the open hardware Arduino-based *RAMPS* control and drive electronics (see http://reprap.org/wiki/RAMPS_1.4) and open source *Repetier* firmware (see http://repetier.com) are used (unmodified).

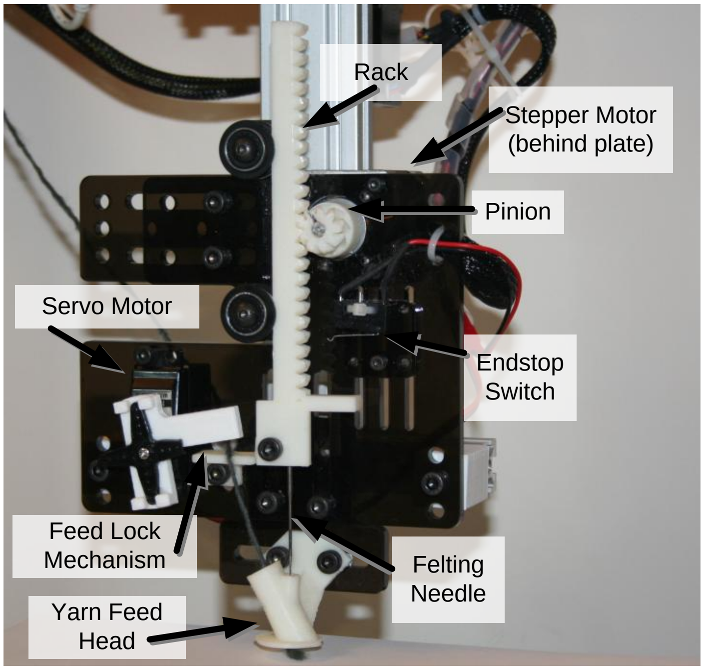

Figure 3. Needle Felting Print Head. The dark mounting plate is laser cut acrylic, while white parts are 3D-printed

This process of forming layers, each constructed from material deposited along a path to fill the layer, is tightly analogous to the process used for *Fused Deposition Modeling* (FDM) [4] which is the most common process used for lower-end 3D printing today. (In that process melted thermoplastic is extruded from a nozzle in a thin line along a path which fills the layer. The plastic adheres to the layer below as it cools forming a solid object.) In fact, the process is so similar that we were able to simply attach our custom print head to an existing FDM printer (initially next to the plastic extrusion head, which we also used to separately 3D print some of the parts forming the early prototype) and directly employ an existing open source slicing and path planning program for FDM printing (*Slic3r*, see http://slic3r.org), augmented with custom translation software as a post-processor, to drive it.

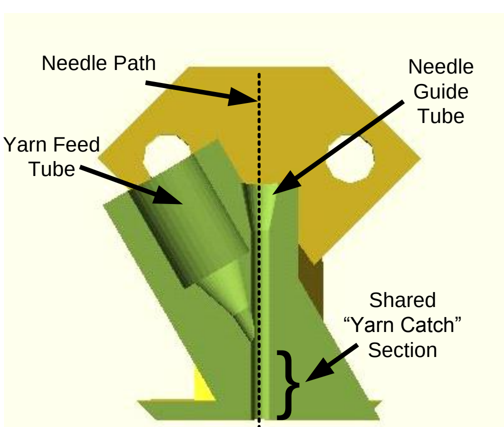

Figure 4. Cut-Away View of Yarn Feed Head.

On the (200x200mm) bed of our printer we use a 50mm thick block of *felting foam* – a coarse, open pore, foam rubber which absorbs needle punches well without degradation. This is topped by a sheet of manufactured felt which provides a body of "starter fiber" for the first printed layer to entangle with. The final print may be carefully peeled away from this base felt, or it may be cut to shape and left in place for added strength. The resulting prints are soft and flexible. They feel somewhat like hand-knitted material, but in 3D solid, rather than flat form

Print Head Details

Figure 3 shows the felting print head which is the heart of the printer described here. The primary action of the print head is to drive a felting needle up and down through the incoming yarn and into the base of previously printed fibers. This reciprocal motion is provided by a rack and pinion driven by a stepper motor. A double helical (or *herringbone*) gear tooth pattern is used to reduce alignment issues and allow wider construction tolerances, and an *endstop switch* is used to establish a home position for the rack. The felting needle is attached to the end of the rack and moves up and down within a custom 3D printed feed head whose interior geometry is shown in Figure 4. This feed head allows new yarn to enter along the tube angled to the left. The yarn then joins a 2mm diameter tube guiding the needle and is contained there with the needle for a length of 8mm until it emerges through a hole in the center of the foot. This area where yarn and needle are together in a tightly confined space helps ensure that the barbs on the needle catch some part of the yarn on their trip down.

To regulate the entry of yarn into the feed head a *feed lock* mechanism controlled by a servo motor is used. This mechanism either allows yarn to travel freely from a low friction spool (behind and above the print head) or stops the feed of yarn entirely by pinching it between two gripping bars. This mechanism serves a purpose somewhat analogous to tension control in a conventional sewing machine in that it allows an appropriate amount of yarn to enter the machine for each step along a printing path. However, conventional uniform tension was found not to work in this case. Our experimentation with early versions of the printer showed that a very low friction feed of yarn is critical while the head is in motion between steps, and for the first needle punch of a printing step. This is because even small amounts of tension on the yarn feed will create a tendency for the previous felting location to "pull out" rather than feeding new yarn in (this is in contrast to conventional sewing where this pull serves to tighten a knot in the stitch). On the other hand, the yarn must not feed continuously, as each of the multiple needle punches necessary to properly felt the yarn into the layer below would pull in new yarn. Our experimentation showed that this creates felting paths which "bunch up", rather than producing a single smooth line of material.

Tensioning which varies during the felting process is accomplished by opening the feed lock before the printer is moved to the next step location, and closing it after the first punch of the needle, leaving it closed for the remaining punches which serve to "felt in" the yarn at that spot. In addition, we regulate the amount of yarn drawn in by the first punch by making it a bit shorter than later punches (pushing the first needle barb 6mm below the foot as opposed to 10mm for later punches).

The printing paths produced from a 3D model by the slicing software are made up of a series of "G-Code" commands for linear movements (originally targeting a conventional FDM 3D printer), some of which also contain commands for extruding plastic, and some of which do not. We use a custom program to translate these commands into modified G-Codes appropriate to drive our machine. In particular, non-extruding moves (and other commands) are tracked, but passed on to the movement controller as is, while each extruding linear moves are translated into a series of felting steps. We use a step size as close to our target step size (currently 2mm) as possible and still produce an integral number of steps per line. At each step we do the following:

1. Move to the step location
2. Initiate the punch sequence with control line pulse *Performed by independent print head controller:*
    2.1. Perform an initial (short) needle punch
    2.2. Close the feed lock
    2.3. Perform N (currently 3) full length felting punches
    2.4. Open the feed lock
3. Wait for the punch sequence to complete

Parts 1,2, and 3 are performed by the unmodified control board (and firmware) of the original 3D printer. While parts 2.1-2.4 are performed by custom drive electronics (and firmware) for the print head when triggered by a pulse on a control line connecting the two controllers. (The Repetier firmware we used provides G-code commands for setting the state of unused I/O pins on underlying the Arduino compatible micro-controller it runs on, so this pulse can be initiated through G-Codes alone without modification to the original printer firmware.)

As currently configured, a punch sequence takes just under 1 second (including 100msec to open or close the feed lock and 195msec for each full length punch). Moves between felting steps can be performed quickly, resulting in a printing rate of approximately 2mm per second.

One important limitation of the current prototype print head is that it does not have a mechanism for cutting the yarn. Feeding extra yarn during non-felting moves often just requires a bit of additional "clean up" after printing (most extra yarn ends up interior to the object and is just invisibly felted over). However, in some cases previously felted yarn can be "pulled up" during a long move. So to temporarily compensate for this missing feature of our prototype, our G-Code translation software can optionally insert pauses before long moves with a prompt to manually cut the yarn. We intend to introduce an automatic cutter based on servo actuated scissor blades in our next round of prototype development.

Material and Printing Details

Needle felting most typically uses unspun fibers (*roving*) rather than yarn because the spinning process makes the fibers slightly less available for entanglement (they are already partially entangled with other fibers in the strand). However, yarn has the significant advantage that it can be easily spooled and fed through the printing mechanism in a controlled and consistent fashion. Nonetheless it may be useful in future work to consider mechanisms which can handle pencil roving rather than yarn.

Yarn used for the printer must be suitable for felting. Yarn made from animal hair, most notably wool, is the most suitable material due to the micro-structure of its fiber surfaces. However we have also had good success with wool blends which include at least 50% wool. Synthetic yarns not blended with wool (such as acrylic) appear to be unsuitable for felting because the very smooth micro-surfaces of the fibers do not entangle well. We also found cotton fibers to be wholly unsuitable and "superwash" wool (which has been treated to improve washablity) does not perform well. Overall we found that less tightly spun yarns with a lot of loose fibers – what might be described simply as "fuzzy" – produced the best results. However, the difference between the best and worst results for a particular fiber type were not found to be as dramatic as differences in fiber type – specifically all (non "superwash") wool and most wool blend yarn we tried felted quite well.

Because yarn is soft, inherently variable, and is compressed during printing, accurately measuring of the diameter of yarn to establish the proper thickness of layers is a bit difficult. Most of the yarn we experimented with was approximately 2mm in diameter (as measured by calipers) and because printed layers are easily compressed this "round number" worked well for most prints. However, for tall prints (over about 50mm) sub-millimeter inaccuracy in the layer height is compounded. We found it was necessary to empirically determine the best layer height for these tall prints. For example we determined that the yarn we used most often printed best in tall prints using a layer height of 2.25mm instead of the 2mm.

Due to the comparatively large thickness of the material being depositing (e.g., 2mm in comparison to 0.5-0.2mm or less for FDM printing) dimensional accuracy is inherently more limited than in other forms of 3D printing. In addition to this inherent limitation we also found that the flexibility and compressibility of the material also contributed to inaccuracies in the result. For example, we found most prints tended to push ~2-4mm outward from the nominal edge of the specified geometric model due to the felting process in layers above somewhat "squashing" the layers below. Further, this type of effect does not occur evenly. This results in an overall randomness of the result which makes its character much more like hand knitting and much less like tightly woven manufactured cloth (or even manufactured felt). While this change of character can be seen as one of the interesting and desirable properties of the result, it also limits the *feature size* of things that can be printed with this material. For example, the solid model for the test bear shown in Figure 1 contains features for a small nose and eyes (8mm and 4mm wide respectively). However, these end up fairly indistinct in the final result.

Due to the flexibility of the material we were initially concerned that we would be unable to print taller objects. However, in our tests we found that we could successfully print objects up to the limit of our initial prototype machine (75mm tall) as long as they were not too narrow. For example we printed a 50mm diam x 75mm tall cylinder without much difficulty (once an accurate layer height was determined). However, for a similar 30mm cylinder we encountered some distortions at higher layers from the "wobble", and large problems for a 20mm cylinder.

As in several other types of 3D printing, the geometry of printed objects cannot be completely arbitrary. In particular, geometry containing *overhangs*, where part of a layer has little or no material in the layer below it, can be problematical since at the limit the layer can be "printing over thin air". This same limitation applies to e.g., FDM printing. For FDM printing this can be overcome by printing extra sacrificial *support* material which is removed in a post-processing step. Even without support material, overhangs of up to 45° can typically be supported (45° is the theoretical tipping point at which the center of gravity of an overhanging flat object is outside the profile of an identical object below it). In fact in FDM printing overhangs of a bit more than 45° can sometimes be printed without support due the adhesion of the material when it is hot.

While the felting printer can also print extra material to provide support for overhanging elements of the geometry, it can be a tricky to determine exactly what material should be removed and remove it without damage to the layers above. To determine how much overhang can be tolerated without support, we performed tests on objects with increasing overhang angles. We found that as the overhang increased deeper layers would get pushed out farther from their intended locations resulting in a gradual degradation of the shape away from its intended geometry. However, this gradual degradation also allowed overhang angles up to 55° in our tests to print without failure (which usually manifests itself as a tangle of unfelted yarn).

Post-Processing

After printing is complete a number of post-processing steps may be performed. The first of these is a set of *cleanup* steps. Since our prototype printer does not yet contain a yarn cutter, extra lengths of yarn will be left with the model in places where the print head moved from place to place without felting down the yarn. Many of these will occur inside the solid model. However, the remainder can be easily removed with scissors. In addition, the imprecision of the printing process (partially resulting from lower layers in some cases being "squashed" or pushed aside somewhat by layers above them) can sometime leave the outside perimeters of layers with small loops or bulges. If desired, these can be "tidied up" by trimming with scissors and/or a bit of hand needle felting work to bind stray yarn more tightly back into the body of the print. Note that these cleanup steps are very much analogous to the kind of trimming and sanding work that is very often needed to clean up FDM printed plastic models on typical lower-end printers.

In addition to cleanup steps it is also possible to increase the tightness of fiber binding within the resulting felt and the overall density of printed objects by agitating the objects in hot water (typically along with a surfactant such as mild soap). Our experiments show that this makes the resulting objects considerably firmer. However, the wool fibers making up the object also shrink changing the dimensions of the object. Considerably more experimentation is needed to properly characterize these effects and of course this post-processing may be problematical if embedded electronics are used.

FUNCTIONAL AND STRUCTURAL COMPONENTS

Printing of custom solid soft objects provides an interesting new capability in and of itself. However, to take full advantage of this capability for innovative interactive devices, we would like to integrate additional electronic and mechanical components and may also want to manipulate the structural properties of the resulting object. In this section we consider some of these aspects. Considerable e-textiles work has been done which shows e.g., how to integrate electronic components with fabric objects. Much of this work is applicable in this domain as well and can largely be reused. Consequently, we will not cover it in detail here. For example, it should be easy to stitch in areas of conductive thread to create capacitive touch sensors [5]. In this section, we will instead concentrate more on aspects which are mostly unique to the nature of this work such as its 3D form.

Cavities and Embedding

To explore the full potential of soft printed objects as a form factor for interactive devices we would like to embed electronic components for sensing and display, as well as motors and mechanisms for actuation within the material. Unfortunately, many of the components we might like to embed would not seem to be very compatible with repeated strikes from a very sharp motor-driven needle. For example, it would seem a normal printed circuit board would likely bend or break the needle (or at least forcibly alter its z-position and ruin subsequent felting punches), while the needle might puncture and damage softer components such as typical flexible circuit materials and some conductors.

To address this challenge we have developed several different embedding mechanisms which can be used in different circumstances. In this section we consider five methods: *Sew in/on later*, *Deep pocket embedding*, *Direct felt-over*, *Capped pockets*, and *Nylon braid tunnels*.

The simplest solution, and one used by most previous fabric-based devices, is to simply sew components onto or into the body of the felted object after it has been constructed. For example circuit boards and other components can be sewn on the outside of the object, or under a sewn on flap. Also because the material is soft and fibrous, a sewing or yarn needle can be used to pull conductive thread through a considerable depth of material (limited only by the length of the needle), or from the surface of the material to an interior cavity (see below). This would allow, for example, components such as LEDs sewn onto the surface, to be easily connected to interior components such as a micro-controller. In fact, due to the pioneering fabric-based interface work of the past, a range of electronic components specifically designed for sew on use are currently available commercially (see for example the over 100 E-Textile products listed for sale at: https://www.sparkfun.com/categories/204).

Since both the exterior and interior geometry of an object can be fairly arbitrary, it is also possible to create interior cavities or *pockets* to hold components. With this approach, an interior void is specified in the object geometry. When the print reaches some number of layers past the bottom of this void, it can be paused. Then a component can be placed in the partial or complete pocket, and the print continued, forming layers over the top of the pocket.

However, the nature of the printing process constrains this approach. In particular, to create good felted bonds between layers our experimentation has shown that the felting needle should generally penetrate 15mm into the material (this includes 5mm of needle which has no barbs and approximately 5 barbs on the next 10mm of the needle shaft). This means that for hard or vulnerable components (such as printed circuit boards) there must be a 15mm gap between the top of the component and the top of the pocket. Since we generally cannot “print in mid-air” over large unsupported areas, we accomplish this by placing a small piece of foam or other “stuffing material” (such as polyester fibers or even simply yarn) in the 15mm void above the embedded component. Printed layers at the top of the deep pocket then felt into this support material and the needle does not strike the embedded component.

This *deep pocket* approach to embedding is suitable for large prints which can contain a ~20mm tall interior void. However, for thin objects this is unlikely to be a viable option. For these cases we can consider several other approaches.

First, based on our experiments we have determined that it is possible to simply *felt over* a few more types of objects than is immediately apparent. For thin wires (stranded insulated wire, solid insulated or bare wire, as well as typical through-hole component leads up to approximately 1mm in diameter) our experiments show that they can be simply placed on top of a layer in a paused print, held loosely in place by hand or with pins, and simply felted over. Our observations show that when the thin needle strikes these objects they simply shift slightly to one side to allow it to pass (although in a few cases the needle bent the wire slightly rather than simply shifting it). Similar results were also obtained with conductive thread. We did not see thread breakage in our tests. We also have not observed spurious conductivity between felted in conductive threads crossing at right angles and separated by a layer of felted yarn. However, we do not feel our tests at present are exhaustive enough to determine that this will always avoid shorts.

In a “torture test” we also successfully felted over a 2.5mm wide nylon wire tie. In this case the needle hit the wire tie on every pass across it and was unable to shift it out of the way in most cases. However, due to the flexibility of the wire tie itself and the compressibility of the 50mm foam pad on the bed of the printer, the material was depressed enough to avoid breaking the needle or causing its motor to skip steps, and the print continued successfully. This indicates that the *direct felt-over* approach may be more viable than immediately obvious. However, more testing is needed to define the range of its applicability.

For cases where direct felting-over is not viable, we have developed a more involved *capped pocket* method which allows objects to be placed in pockets no deeper than the embedded object so long as the pocket can be placed within a few printing layers of the top of the print (or an indentation at the top of the print is acceptable). To do this, we first separately print a thin *cap* consisting of a felt base with one or two layers of yarn felted on top of it. The felt is cut with a ~4mm “lip” sticking out past the printed yarn layers. In the main object we use a pocket geometry illustrated in the cutaway view of Figure 5 (top). The print is stopped one layer above the top of the pocket, the embedded object is inserted, the previously printed cap (with its felt base) is placed on top, and the print is continued. The remaining layers then felt through the cap lip and abut the cap yarn layers. This results in a surface covered with felted yarn as shown at the bottom of Figure 5, but is formed in a way which never has the needle intrude into the embedded object’s pocket.

A final method for embedding objects can be used if small embeddings away from the print surface are needed and objects can be inserted from the side after printing, or when long passages are needed (e.g., for multiple wires or even

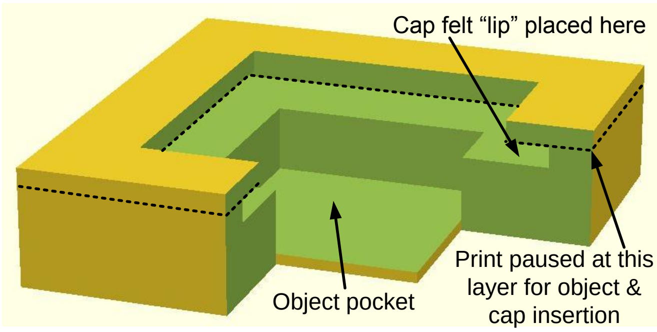

Figure 5. Cutaway view of capped pocket internal geometry (top), and resulting cap surface (bottom).

thick cables). This method makes use of flexible nylon braided tubes which are sold for use as wire bundle covers. In this case, the print is paused, and the nylon tube is placed on top, then loosely pinned or held in place. The print then continues, felting the tube in place through the braid, first with one layer only at the edges, then fully over the tube (see Figure 7). After printing is complete, the interior of the tube can be partially cleared of fibers with e.g., a small screwdriver shaft, and then objects may be inserted into the relatively slippery nylon tube. To accommodate thicker objects the layers above and below the tube can be constructed with small gaps or holes to allow more room for the tube to expand (and partially displace those layers). Figure 8 shows the use of this type of *nylon braid tunnel* as part of a flexible bend actuator.

Bridging Between Hard and Soft Materials

In order to fasten printed objects to most types of materials it is necessary to bridge between hard "external" materials (or fasteners) and the soft felted material produced by the printer. Such a bridging is also necessary if internal motors or other actuators are to be embedded in the object to move it, since the solid actuator must push or pull the felting. Unfortunately, the felting which results from the printer is not as strong as e.g., typical fabric. In addition, we do not necessarily have the ability to apply reinforcement techniques developed in that domain such as the extra stitching around button holes. As a result, when forces end up being transferred from e.g., an attachment point with a bolt, rivet, or other solid connector, into the printed object, it is often not (at least in the long run) strong enough, and will tend to (eventually) rip out.

In order to address this issue and provide more usefulness for resulting printed objects we have developed a simple technique for bridging between hard and soft materials. This technique involves felting in a layer of nylon mesh fabric to form this interface. The holes in the mesh allow felting fibers to pass through it and be entangled in layers below the mesh. This thoroughly embeds the mesh within the felting and can be done without otherwise disturbing the print (as with other embedding, fibers of the mesh appear to shift slightly when they happen to be struck by the thin felting needle). Since the mesh stretches slightly (but less than the felting) this allows any forces on the mesh to be distributed over the whole area where it is embedded. Specifically lateral forces on the mesh will be transferred to the fibers of the felting at the boundary of nearly every hole in the mesh rather than being concentrated in a small area, e.g., immediately around a hard connection point.

This leaves the problem of attaching hard objects to the nylon mesh. The nylon mesh is much stronger than the printed felt and in many cases is sufficiently strong to attach to directly. However, to provide more robustness for attachment and allow us to also spread out the forces applied from a hard object into the mesh, we have developed a double embedding technique.

This technique embeds the mesh within the plastic of a 3D print (created with an FDM 3D printer, in our case printing PLA plastic). Figure 6 (right) shows an example of this. Here we have constructed a large grommet around a 5mm mounting hole which is embedded in a patch of nylon mesh.

To construct this embedding we create a solid model for the grommet which leaves a small (1 layer) gap for the mesh. The layers below the mesh are printed. The print is then paused and the mesh taped in place over the partially constructed grommet. The print is then resumed (with the printer having skipped the layer containing the mesh as specified in the solid model) to print layers of plastic over the mesh. This results in an embedded patch of mesh which is tightly bound to the plastic layers surrounding it. A mesh patch prepared in this way can then be felted into an object printed on the felting printer using one of the embedding techniques described in the last subsection.

For our experiments with this technique we used a nylon mesh with ~2mm holes which appears very suitable for embedding both in the FDM deposited plastic and the felting. The mesh is ~0.2mm thick. However, to provide clearance for potential unevenness in the mesh and/or very small wrinkles we used a 0.4mm layer height in the FDM print (hence leaving a 0.4mm gap for the mesh). When initially deposited, the hot thermoplastic seems to flow over and through the mesh, including any small irregularities, and bonds firmly with the plastic in the layer below. We found that two plastic layers below and two plastic layers above the mesh were quite sufficient to create a solid

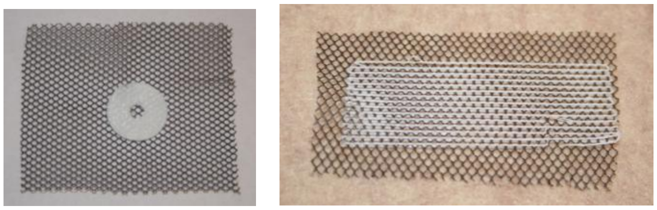

Figure 6. (Left) Nylon mesh interface layer embedded in a 3D printed hard plastic grommet (with 5mm mounting hole). The nylon mesh can then later be embedded in a felting print to provide a smooth distribution of forces applied to the grommet across the many fibers felted through the mesh. (Right) Custom 3D printed stiffening sheet.

mounting, but thicker and more varied geometries could be used.

This technique is particularly flexible because the solid model for the plastic part of the interface can be specified to directly mate with the mounting holes and/or other geometry of the specific part being attached or embedded. We also have flexibility in how much mesh surface is used to absorb and distribute forces and can tailor that surface area in the direction(s) we expect forces from the hard/soft interface to be applied from.

Manipulating Stiffness

A final area we explored was manipulating the stiffness of printed objects. This is useful for example, for creating joints within articulated characters or foldable devices. There we would like the joint to be more flexible than the material adjacent to it so that bending occurs at the joint rather than elsewhere.

For this purpose we looked at three techniques. First we can increase the flexibility of the resulting printed object by leaving small gaps in the geometric model used to create it. This causes the creation of small voids which bends can collapse into.

To increase stiffness we looked at two techniques. In the first we placed a layer of low stretch fabric within the print. This fabric was felted into the body of the print, with fibers from the layer above the fabric passing through it to felt with the layer below.

In our experiments we used a thin nylon organza fabric – essentially a very thin woven nylon mesh. The properties of this particular fabric cause it to be both amenable to felting fibers through, and exhibit low stretch. However, many other fabrics could likely be used for this purpose.

Since the fabric was less stretchable than the felt that was formed through it, it resisted bending somewhat more than the surrounding felt, thus somewhat increasing the stiffness of the area it was embedded in. Additional layers of non-stretch fabric can be embedded to increase stiffness. This allows us to create a range of different stiffnesses to meet different needs. It also allows the stiffness of an object to shift incrementally across an area rather than changing at a single point from most to least stiff.

However, we found that this sort of fabric stiffener could only increase stiffness to a low to moderate degree. To achieve more stiffness (and make it easier to place and tailor stiffness at modeling time) we also experimented with the creation of custom stiffening sheets. In this technique we again used nylon mesh embedded in 3D printed plastic.

In this case we printed a series of thin lines bonded above and below the mesh as shown in Figure 6 (right). This material is constructed from a solid model with the same mesh embedding procedure described above. These lines were designed to be narrow enough (and widely spaced enough) that they could be easily felted over – like other narrow objects we tried, the lines appear to shift slightly rather than break if they happen to be struck by the needle. Sheets of this type can then be felted into the body of a print to significantly increase stiffness where desired. Like the hard/soft material interface described above, the use of an embedded mesh allows forces to be distributed across an area, making the presence of a stiff material inside a soft one less problematic. Because the stiffeners are 3D printed, the exact placement of stiff versus flexible regions can be easily specified as part of the solid model for the stiffening plastic. Further the exact stiffness can be varied by leaving alternating gaps in the lines and/or manipulating the space between them. This allows us to very finely manipulate the details of stiffness properties and thus to create objects which can be highly tailored to their intended use. For example objects on the outside of clothing can be made to bend where they need to for comfort, while being more ridged in other locations.

For our experiments with custom stiffeners we used the same nylon mesh as our hard/soft material interfaces. Like those tests we used two 0.4mm layers below the mesh, a 0.4mm gap for the mesh itself and two layers above the mesh. We deposited the thinnest lines available on the printer (~0.4mm wide).

As is evident in Figure 6 (right), the resulting print typically contained some flaws. These were caused in two ways. First the very narrow lines did not respond to unevenness in the mesh well in a few places. In particular, the extruded plastic bead did not have plastic next to it which would help to hold it closer to its intended position when irregularities occurred. Second, the very narrow separated lines stuck nearly as well to the printer bed as to the mesh and layer above, and so in a few spots the layers delaminated when they were removed from the printer. Also, although inconclusive, our experiments raised questions about the long term robustness of the printed stiffeners – whether the thin lines might break over time and hence decrease stiffness. Our tests were done with PLA thermoplastic. However, it is likely that nylon would be a more robust material to deposit for this purpose.

EXAMPLE USE

As an illustration of how the techniques described above can be brought together to create functional interactive

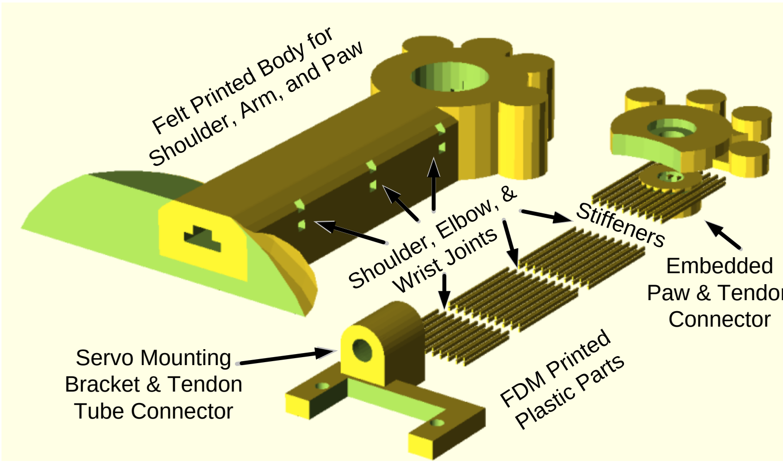

Figure 7. Exploded view of a geometric model for articulated arm example. The shape at the top left is printed on the felting printer, while the shapes along the lower right are 3D printed plastic parts, several of which are designed to include embedded nylon mesh. These plastic parts are embedded inside of, or attached to, the felt component to form the final functioning arm which bends smoothly at shoulder, elbow, and wrist joints.

Figure 8. Partially printed arm example showing embedded components. Here we can see an embedded black nylon mesh tube (left) which holds a yellow tendon wire. This wire loops around a bolt which attaches the (white) assembly under it that is being printed over at this point. This assembly contains an embedded metal nut, nylon mesh to spread forces from the hard attach point and 3D printed stiffening material.

objects, this section describes the design and construction of a partial prototype for an articulated soft object. In particular we consider an internally articulated arm which could be part of an interactive teddy bear. This example combines embedding, hard/soft bridging and stiffness manipulation to create a soft arm which bends smoothly under control of a servo motor (which could in term be driven from an embedded microcontroller which could e.g., capacitively sense touch using conductive thread). Figure 7 shows the solid model which was used to print each of the parts making up the final object which is depicted in Figure 9. The form in the upper left of Figure 7 is the felted portion of the print which was printed on the felting printer. The parts arrayed on the lower right are printed on an FDM 3D printer. Several of these parts are designed to be embedded over nylon mesh as described in the last sections. These parts include: a mounting bracket which connects a servo motor to a polyethylene tube which in turn connects to a nylon braid tube (not shown); stiffening elements with gaps to support bending preferentially at shoulder, elbow and wrist joints; and an embedded connector (with embedded metal nut (not shown)) which attaches a tendon wire to the paw plate with a small bolt (not shown). The tendon wire runs from the servo motor to a solid attachment point under the paw plate. When this wire is retracted the arm bends (up) at the shoulder, elbow, and wrist joints formed by gaps in the stiffener as well as voids in the felt. The full assembly arrayed in the lower right of Figure 7 is embedded inside (or attached to) the felt shown at the upper left as it is printed. Figure 8 shows some of this embedding part way through the printing process, while Figure 9 shows the final result.

This example illustrates some of the range of structures which might be combined to create fully interactive soft devices. Although this example requires multiple components and some assembly by hand placement of embedded objects (and attachment of a bolt), each of these parts can be specified and manipulated in a purely virtual solid model and can be printed on demand. This allows for very rapid exploration of a space of prototypes which would not be possible without the use of this technology.

LIMITATIONS, CONCLUSION AND FUTURE WORK

This paper has demonstrated the basic capability to 3D print objects in a soft material composed of needle felted yarn. This new material opens up many new possibilities for 3D printed objects and extends the domain of 3D printing from primarily hard and precise objects into a domain which can include soft and imprecise objects. This allows the exploration of a very different design aesthetic while still allows the many advantages of additive manufacturing techniques. These include the ability to rapidly move from ideas, through virtual geometric models, to physically realized forms. In this case we are able to design objects with mature solid modeling tools, and then print these objects in a few hours. This can be contrasted with roughly equivalent hand knitted objects which do not have similar design tools (at least with respect to their 3D characteristics) and would take days to create.

Figure 9. Final printed arm

However, the work presented here is only a beginning. The printing technique described here has several limitations and considerable future work is still needed. Perhaps the most important limitation of this technique is the physical robustness of the resulting felted objects. These objects exhibit reasonable strength for forces applied laterally to layers. However, they are less robust to forces perpendicular to layers, tending to pull the layers apart. To improve robustness in that direction in future work we may consider injecting very small amounts of a flexible adhesive in conjunction with the felting process in order to more permanently bind felted fibers between layers. However, considerable experimentation will be needed to find an appropriate adhesive and application process. In particular, a balance will need to be struck between adhesion and resulting stiffness if the soft character of the results are to be maintained.

Although imprecision is in some sense a desired part of our result, another limitation of the technique is that it may be too imprecise for some uses. Finally, we feel that considerably more exploration is needed in designing new types of mechanisms, structures, and electronic sensors, within, around, and with this new material.

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