A METHOD FOR CREATING ACTUATED JOINTS VIA FIBER EMBEDDING IN A POLYJET 3D PRINTING PROCESS

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ABSTRACT

The Objet PolyJet direct 3D Printing process is capable of simultaneously depositing two distinct photopolymer materials in preset combinations to enable designers to create parts with graded material properties. For example, this dual-jet process offers designers the ability to combine elastomeric and rigid materials in order to create integrated assemblies featuring stiff components and flexible joints and gaskets. To expand the potential of this technology, the authors have developed a method for the direct fabrication of systems with actuated joints without post-process assembly. The method, which involves temporarily pausing the build process and embedding and anchoring fibers into the part, is described in this paper along with part design considerations. Two systems featuring actuated joints are presented as a means of displaying the embedding method's capabilities.

Keywords: PolyJet™ Process, 3D Printing, Actuated Joints, Fiber Embedding

1. EMBEDDING COMPONENTS VIA ADDITIVE MANUFACTURING

A fundamental advantage of the layer-by-layer fabrication approach found in Additive Manufacturing (AM) technologies is the capability to access the entire volume of the workpiece throughout the build process (Kumar, 1998). This lies in contrast to traditional manufacturing techniques, where one only has access to the external surfaces of the part. As such, AM affords the opportunity to embed components such as circuits, sensors and other functional components (e.g., motors, threaded rods, etc.) into a part as it is being fabricated, thus allowing for the direct fabrication of functional assemblies and mechanisms within the AM machine without the need for a secondary assembly step. This capability provides an opportunity for the realization of such applications as actuated robotic limbs, smart structures with embedded sensors, and energy harvesting devices with embedded piezoelectric materials.

Prior efforts in embedding components into parts are primarily centered in three AM technologies: Shape Deposition Manufacturing (SDM), Stereolithography (SL), and Ultrasonic Consolidation (UC). In general, each process involves creating a custom void for the insert in the built part, pausing the build, embedding the insert into the custom void, and then resuming the build to completion.

1.1 Existing Techniques

Shape Deposition Manufacturing (SDM)

Shape Deposition Manufacturing involves depositing a layer of material then CNC (Computer Numerically Controlled) machining each layer to final dimensions. Layers of either metal or polymer are deposited via arc, thermal, or plasma spraying, laser or MIG welding, microcasting, or extrusion. Microcasting, a technique developed specifically for SDM, involves melting a feed wire into droplets that fall onto the build surface and flatten to form the layer. Selection of support material for use in microcasting is critical, however, since the support material must have a lower melting temperature but higher thermal conductivity than the build material (Weiss et. al. 1997). Researchers at Carnegie Melon University used SDM with microcasting to create three-dimensional circuits for use in wearable computers (Finger et. al. 1996, Smailagic et. al. 1993). The embedding process begins with machining a pocket for the insert, embedding the insert into the pocket, and the resuming the SDM procedure above the newly embedded part.

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Li et. al. used SDM in conjunction with laser sintering to embed optical fibers and fiber brag sensors for measuring the internal stresses in laser-assisted SDM. First, a stainless steel substrate was created with a cavity for the fiber. After inserting the fiber, a stainless steel powder is deposited onto the fibers and melted by a laser to form the layers. Finally, SDM was employed to attain the desired dimensions of each layer (Li et. al 2000, 2001, 2003). Similar fiber-embedding using laser-assisted SDM has been accomplished by Golnas "to monitor in real-time thermo-mechanical responses of tools, equipment, and structural equipment" (Golnas 1999). As with Li's work, fibers were embedded into stainless steel by laser sintering a powder above and around the fibers, and subsequent machining accomplished the desired layer dimensions (Golnas 1999).

Researchers used SDM to manufacture biomimetic robots with sensors, flexible joints, and pneumatic actuators embedded into the structure. Through a sequence of creating molds, bulk-depositing epoxy and other polymers, machining, and embedding components, robotic parts were created with embedded pneumatic actuators, servo-motors, flexible inserts, and other components. "Sprawlita," a robust, insect-like robot with flexible joints made exclusively of embedded components, was created using this process (Bailey et. al. 2000, Cham et. al. 1999 and Cham et. al. 2002). Hatanaka et. al. developed a similar process that combines photolithography with SDM to embed flexible components, such as fibers, fabrics, and electrical wires, for creating polymer mechanisms with flexible joints. This was achieved by first creating the polymer stucture and cavity by SDM and then anchoring the fibers with a photopolymer that is selectively cured via masking a UV light scource. Bulk material was then deposited around the secured ends of the fiber to create the remainder of the structure, and SDM was employed to create the desired surface finish. A two degree-of-freedom gimbal with fiber flexures was created using this technique, among other mechanisms (Hatanaka et. al. 2003, Hatanaka 2005).

Stereolithography (SL)

The stereolithography process uses a vat of photopolymer that is cured with an ultraviolet laser in a layer-wise fashion. The void for the insert is created in each layer by design, the build is paused, the insert is press-fit into the void, and the build is resumed over the top of the insert (Kathryn et. al. 2002). Initially, this technology was used to embed sensors (Nau 1991). Since then, Geving has embedded larger components in SLA builds, such as a screwdriver that was embedded in a SL build (Geving 1999 & 2000). Subsequent work involved standardizing and process planning for embedding complex components to create functional assemblies and mechanisms, which involved the use of functional inserts and shape converters (Kataria et. al. 2000 & 2001, Kataria and Rosen 2001, Laio et. al. 2007). A functional insert is a solid member that is not made from additive manufacturing (AM), such as a motor, gear, bearing, wiring, etc. A shape converter is a solid member made from AM that is designed to fill the space between a printable cavity and the contours of a complex shape. Shape converters are used for objects which, if embedded, would cause laser-shadowing, undesired vacancies, or undesired submerging of components in the polymer resin. Kathryn and Kong demonstrated the value of using shape converters by creating a small, remote-controlled vehicle made of entirely SL-embedded components (Kathryn et. al 2002). Finally, another process for embedding in SL was developed to create embedded electrical systems by combining direct writing of circuits and stereolithography. This hybrid process worked by first pausing the SL build, using a direct write (DW) device to extrude a conductive paste onto the layer in the pattern of the desire circuit, and then resuming the build to embed the printed circuit. (Palmer et. al. 2005, Medina et. al. 2005, Lopes et. al. 2005).

Ultrasonic Consolidation (UC)

Ultrasonic Consolidation creates nearly fully dense metal parts by ultrasonically welding foil sheets of material together and then CNC machining the layer to final dimensions (Siggard et. al. 2006). Much like SDM, the embedding process involves CNC machining a pocket for the insert, embedding the insert, and then resuming the UC additive manufacturing process over the insert. Electronics and sensors have been embedded in UC builds to shield them from space and other harsh environments (Siggard et. al. 2006). Composite structures were created that contained shape memory alloy fibers, optical fibers, and reinforcing fibers (Kong 2011, Choon et. al. 2005, Yang 2008). Ram et. al. investigated the compatibility of varying combinations of differing metals, such as aluminum-copper alloys, nickel based alloys, and stainless steel in UC and found that "most of the materials investigated could be successfully bonded to Al 3003 and vice versa" (Ram et. al. 2007). Finally, DW technology has been integrated by Robinson et. al. into UC to create an aluminum panel with embedded circuitry (Robinson et. al. 2006).

Other Processes

Selective Area Laser Deposition (SALD) uses a laser beam to decompose a gas into a solid deposit, which is fused to preceding layers. Inserts can be embedded, as with SLA, by creating a void in the part design and inserting the member into the void. Sun et. al. used this process to create and embed "psuedo thermocouples" into layers of alumina and silicon carbide (Sun et. al. 1998, Sun et. al. 1999).

Laminate Object Manufacturing (LOM) was utilized in conjuction with the previously mentioned functional inserts and shape converters to embed components including a fan, motor, and battery arrangement. Formerly, a LOM build entailed a significant post-processing stage in which the excess material was manually removed after the build was complete, precluding the manufacturability of hollow or complex parts. However, Liao et. al. enlisted a special removal algorithm to remove support material during a LOM build, enabling the creation of hollow features and therefore enabling embedding to take place in the voided areas (Liao et. al. 2006).

1.2 Context

While the reviewed AM technologies have been used to create mechanisms via embedding, geometrically complex parts with actuated joints are not capable of being fabricated without a siginificant amount of planning and assembly. In this paper, the authors look to expand the potential of additive manufacturing technology by exploring a method for the direct fabrication of systems with actuated joints without post-process assembly. Specifically, we look to the PolyJet direct inkjet printing process as a means of fabricating actuated joints in a single build session. With the advanced capability of the PolyJet process to accurately deposit multiple materials in a single layer, mechanisms featuring rigid members and flexural joints can be created. The PolyJet process is described in Section 2. The embedding process is described in Section 3. In Section 4, two case studies are presented as a means of displaying the process capabilities. Closure is offered in Section 5.

2. POLYJET DIRECT INKJET PRINTING

PolyJet is a direct 3D printing technique that utilizes drop-on-demand inkjet printing to selectively deposit droplets of photopolymer directly onto a build platform. An illustration of the print head assembly block of a PolyJet printer is presented in Figure 1.

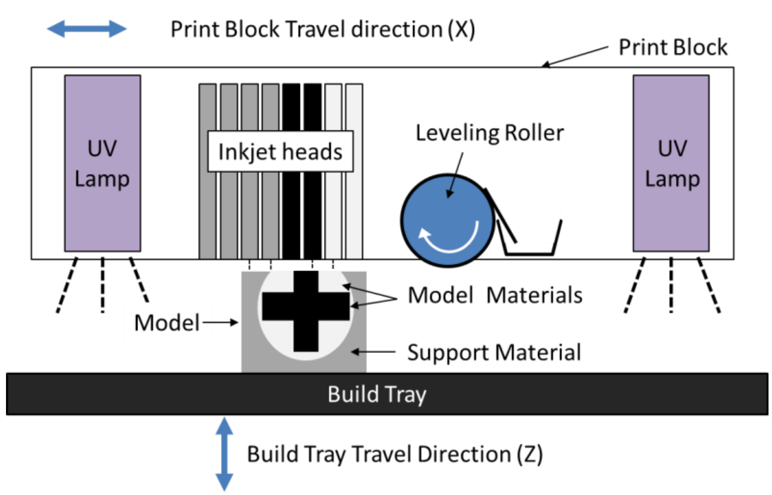


Figure 1. Objet Polyjet Print Head Assembly Block

Once a layer of droplets is deposited (64 μm in standard mode; 32 μm in high-resolution mode), a roller evens out the horizontal surface of the layer, after which two UV lights (one leading and one trailing) pass over the printed layer multiple times to cure the photopolymer. As several inkjet print heads with separate material sources can be installed into the printing block, multiple materials can be deposited in a single layer, thus enabling the creation of graded materials. One of the materials printed is a dedicated a hydrophobic gel that is used as a support material for the fabrication of complex geometries.

The PolyJet process creates new layers by direct material addition, and is thus well suited for component embedding. The lack of a recoating step, wherein raw material is added in bulk in powder or resin form, eliminates concerns of disturbing the previously printed layer typically found in embedding processes.

However, there are two inherent limitations in using the PolyJet process as a means of embedding components. First, as there is not yet a means in the PolyJet software to manually configure the deposition of support material, one must manually remove the deposited support material from the void in which a component will be embedded. Secondly, as the print head assembly block passes over the printed part at a clearance of only 4 μm, embedded components cannot protrude from the previously deposited layer, or damage to the printing nozzles could occur.

3. EMBEDDING PROCEDURE

In this section, a method for embedding fibers into parts created by the PolyJet process is presented. In general, the procedure is as follows:

1. Design guide and fixation channels for embedding fibers into the part. In addition, an identifier marker, to be made from a different material in the print, can be included to alert the user to stop the build.
2. Pause the build and remove support material from designed channels.
3. Embed component into channel.
4. Anchor fiber via deposition, and subsequent curing, of photopolymer.
5. Resume build.

3.1 Channel Design

To prepare for fiber embedding, channels must first be designed into the part. A schematic of a designed channel is presented in Figure 2.

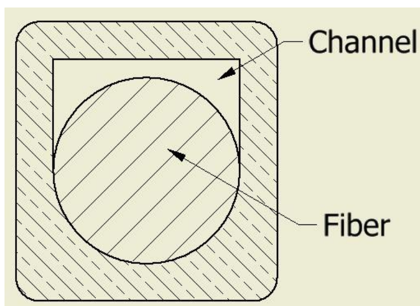


Figure 2. Schematic of integrated channel. Shown is the channel profile used in embedding a fiber of circular profile.

The lower portion of the channel is designed to match the profile of the fiber. The upper portion of the channel is of a rectangular profile at a width equal to the diameter of the fiber. This geometry is necessary as the widest portion of the fiber must be able to pass into the channel from above during embedding. Building a completely circular profile layer-by-layer would prevent the embedding of the fiber.

In initial embedding experiments, the channels' depth was designed to be equal to the diameter of the fiber. However it was found that, due to the machine's delay in pausing the build process, the height of the channel should be larger than the diameter in order to avoid closing the channel top before embedding can take place. As such, channels are typically designed to be 0.005 in. larger than the fiber diameter.

In general, two types of channels are created to allow for fiber embedding:

- *Guide channels*: These channels allow fiber movement within the channel by providing clearance between the channel wall and the fiber.
- *Fixation channels*: In places in which the fibers are to be anchored, the channel width must have very little to zero clearance with the fiber. As such, the fiber is press fit into the channel prior to bonding via the addition of an adhesive.

To determine the appropriate clearances for fiber embedding, a series of preliminary experiments were conducted in which fibers were embedded into channels with varying clearance of 0 – 0.035 in. As can be observed in Figure 3, channels with large clearances resulted in a poor surface finish due to layer build errors propagating throughout the build process. Examination of the resulting surface finish above each channel confirmed that a channel width equal to the diameter of the fiber (i.e., a zero clearance) is ideal for embedding. At zero clearance, the channel is filled by the fiber, and thus provides a proper surface for material deposition.

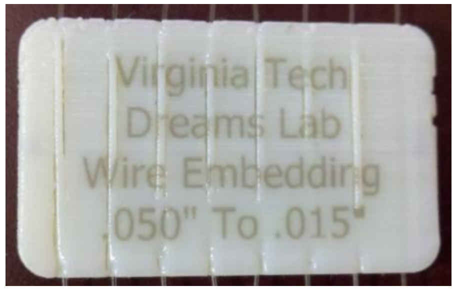
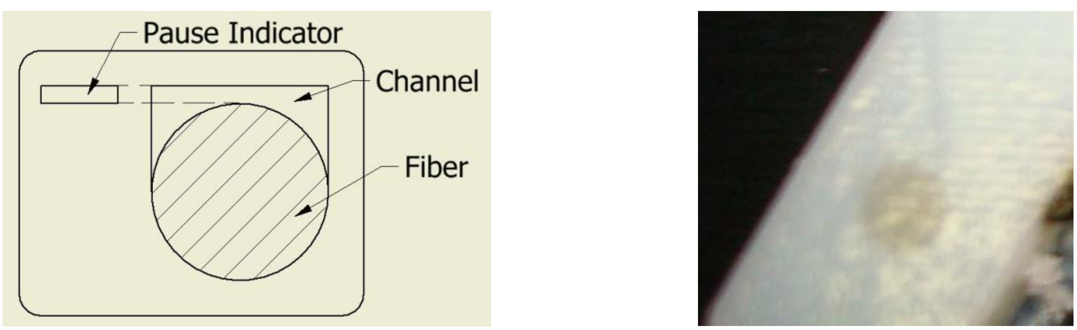


Figure 3. Surface finish test part. The clearance between the fiber and the designed channel is varied between 0.035 inch (left) to 0 inch (right).

3.2 Pausing the Build

As the proposed procedure for embedding fibers is manual, a method for alerting the user to the precise layer in which the build should be paused is necessary. While one can estimate the location of the appropriate layer by dividing its height by the build layer thickness, or by stepping through the layers of the “Build Assembly Map” created by the Objet Studio software, the unique multi-material capability of the PolyJet 3DP offers a more precise means for alerting the user. Specifically, the user can design a feature in the part that can serve as a “pause indicator.” While this type of approach has been suggested in the SL embedding process (Kataria and Rosen, 2000), the unique multi-material properties of the PolyJet process provides a stronger visual cue, as the indicator can be built with a material different than the build material.

In order to create a feature with a different material in the PolyJet process, it must be first modeled in CAD as component of an assembly. This is done by subtracting a volume within the part and creating another part of the same size that is constrained to the cavity. The profile of this cavity in the XY build plane is designed so as to be clearly visible and distinguishable from other nearby features. The depth of the feature should be started at the Z-height of the top of the fiber, and extended in a positive-Z direction to the level of the top of the channel (Figure 4a). The pause indicators created in this work were 0.005 inch. A pause indicator of less than this thickness might not be fabricated by the printer due to the minimum layer thickness imposed by the process. A sample pause indicator feature, which provides a visual indication that the channel has been built to an appropriate depth for fiber insertion, is shown in Figure 4b.



(a) (b)

Figure 4. Pause Indicatorl (a) schematic and (b) implementation . This circle is an example of one of the pause indicators that the machine operator observes to determine when to pause the build. This indicator is a small amount of material that differs visually from the rest of the part material.

There are two means for pausing the Objet system: one on the Studio PC that is used to assemble the build job from the input STL files; the second is on the PC that is integrated into the printer itself. Both methods were used in initial experiments to determine if the source of the pause command affected the behavior of the machine. It was found that, a pause command initiated from within the job manager on the studio PC resulted in a pause after at least three more layers of the part had been deposited. However, a pause command initiated from the PC integrated on the printer caused the pause to be executed after the current layer had been deposited. Both methods also caused the machine to fully cure the recently deposited layer (through three passes of the printing block) prior to the actual pause before the machine lid was able to be opened. Because of its immediate nature the pause command, the integrated PC was used for all embedding experiments. The pause command is issued as soon as the pause indicator is observed.

3.3 Embedding and Anchoring the Fiber

Before the fiber can be embedded into the part, the channel must first be prepared by removing the support material. Unfortunately, support material is automatically added into a part's channels by the Objet Studio software; there does not yet exist a means for a user to control deposition of support material. In order to allow for a proper bond between the fiber and a part, support material is totally removed from fixation channels. Support material is partially removed from guide channels to allow for fiber insertion. Care must be taken to create a groove for the fiber while simultaneously preventing the subsequently printed layers from filling the area surrounding the fiber, as this would bond the fiber in place and would prevent actuation.

Embedding fibers is accomplished by manually placing them into one of the fixation channels. Care must be taken to ensure that the fiber is fully seated into the channel without protruding above the recently printed layer. The fiber is then pressed into the groove formed in the support material of any adjacent guide channels, and finally into the final fixation channel. This process allows fiber insertion with proper initial fiber tension.

Anchoring the fiber to the fixation channels is achieved by first depositing build material photoplymer resin to the fiber-channel interface area, and then exposing it to light at the proper wavelength to cure and harden the resin. To determine the proper curing procedure, the authors first identified the amount of irradiation in the PolyJet printing process. First, it was observed that the high intensity mercury arc lights used in the Objet Connex 350 have primary emission peaks located at 365nm and 254nm. Through the use of a UV dosimeter, it was discovered that the energy absorbed by the material during the printing block's three curing passes is between 240 and 300 mJ/cm^2 at a wavelength of 365nm. As anchoring via photopolymer curing would require a manual approach, the authors investigated portable sources of UV irradiation. A 250 watt halogen bulb was used in initial trials due to its broad emissions spectrum. However significant time was required to harden the resin due to the low spectral output of $20mj/cm^2$ min at 365nm. Furthermore, the light heated the part significantly, which could lead to warping. Better results were obtained by using a CH lighting brand Model F4t5/BL ultraviolet florescent tube in portable battery powered fixture. This portable UV light produced an energy output of 123 mJ/cm^2min at the required 365nm wavelength. Using the results from these measurements it was determined that an exposure of 3 minutes resulted in UV exposure levels similar to those that the resin would experience during the PolyJet build process.

4. CASE STUDIES

Two case studies are presented as a means of validating the proposed embedding approach. The first represents an actuated finger and features a linear fiber path. The second case study is of an actuated leg that features a fiber that is embedded along a curved path and through multiple materials.

4.1 Actuated Finger

As an initial proof of concept, an approximation of a finger with multiple joints and two embedded fibers was designed (Figure 5). A slider and frame arrangement was integrated into the base of the finger to allow for manual manipulation and actuation of the finger. The part is 3.25 inches in length. Rigid members of the assembly were fabricated with VeroWhite material; flexible "knuckle" joints were fabricated with TangoBlack material. VeroWhite was also used as the material for anchoring the fibers into fixation channels.

(a) (b) (c)

Figure 5. (a) CAD representation of finger, (b) As built, (c) Actuated

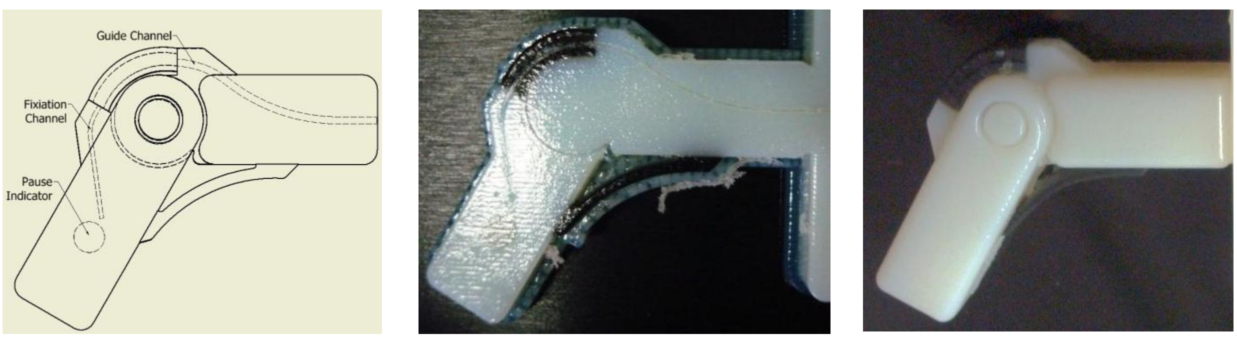
A monofilament strand, with circular profile and a diameter of 0.015 inch, was chosen for embedding. Fixation channels were placed at the tip of the finger and in the slider. The channels had a width of 0.015 inch and a depth of 0.020 inch, resulting in a zero clearance fit. Guide channels were used on two intermediate joints, as well as the base of the finger, to allow fiber movement during actuation. The guide channels have a circular profile with a diameter of 0.032 inch, resulting in a clearance between the fiber and surrounding guide channel of 0.0085 inch.

The embedding process of this part followed the steps outlined in Section 3. The build was carefully monitored and paused when the pause indicator became visible. The fixation channels were cleared of all support material, and the support material in guide channels was grooved, to accept the fiber. The fiber was pressed into the fixation channel integrated into the slider, then into the guide channels, and finally into the fixation channel on the tip of the finger. VeroWhite resin was then applied to the fixation channels manually using a syringe. The liquid photopolymer was then cured via a portable UV light source. Excess support material was then cleaned from the top surface of the part, and the print was resumed to completion. The final assembly with embedded fiber is shown in static (Figure 4b) and actuated (Figure 4c) states.

4.2 Actuated Knee

The actuated knee case study featured in Figure 6 is a more complex mechanism than the finger case study discussed above. As can be seen in Figure 6, the mechanism uses a revolute joint with an embedded fiber for actuation. As the embedding path is curved, and the fiber is completely enclosed within the part, this part provides a suitable example of a mechanism that can only be created via AM. The part is 1.25 inches in length.

The rigid portions of the part are made from VeroWhite material. The fiber guide portion, and inside the "ligament," are produced with TangoBlack, which provides the necessary flexibility and elasticity. The leg is attached to a slider and frame assembly similar to the actuated finger produced previously to allow manual actuation of the assembly.



(a) (b) (c)

Figure 6. (a) CAD representation of knee, (b) in-situ embedding, (c) finished part

A fixation channel (0.011inch wide and 0.0155 inch deep) is integrated into the tip of the leg as shown in Figure 6a. The guide channel used in the rigid portions of the part has a circular profile and a diameter of 0.020 inch. The fiber embedded into this part has a diameter of 0.011 inch which gives no clearance in the fixation channel, and 0.0045 inch clearance in guide channels.

To ease fiber insertion, and to lessen the chances of the fiber moving out of position during the build process, the fiber was pre-formed to the shape of the channel prior to insertion. The fiber was first inserted into the leg tip fixation channel, ensuring the fiber filled as much as possible of the channel to maximize the surface area available for bonding to the part. The fiber was then placed into the guide channels and pressed into the fixation channel integrated into the actuation slider (Figure 6b). VeroWhite resin was then applied by syringe, followed by a 3 minute exposure from the portable florescent UV light source.

Manual actuation of the leg was achieved and it was noted that the tension required to actuate this joint was higher than for the open joints of the actuated finger produced previously.

4.3 Discussion

By achieving actuation in the actuated finger case study, it was proven that the fiber embedding technique is a valid method that produces usable assemblies featuring living hinge mechanisms. The actuated leg case study served to prove that embedding along a curved enclosed fiber path was viable, thus enabling a suite of mechanisms unique to AM processes.

Some features of the proposed process do place limitations on the types of mechanisms that can be created. Due to the layer-by-layer nature of the 3D Printing process, fibers can only be embedded within a single plane. No part of the fiber can protrude above the surface of the part that was being fabricated when the build process is resumed. If any protrusions are allowed to form, the print head will catch upon them as the build process is resumed and the part, fiber, or print heads will be damaged. This places a limit on the complexity of mechanisms that can be created with this process.

Furthermore, the current method of removing support material from the channel prior to embedding is a manual process and depends greatly on the skill of the machine operator as well as the tools used. For optimal results to be achieved, the channel should be fabricated with no support material within. However, the capability of doing this is hindered by the Objet Studio software, which automatically inserts support material in areas that would be required for standard prototype fabrication.

The method used to secure the filament within fixation channels was a combination of a press fit within the channel as well as using a small quantity of manually applied photopolymer resin as an adhesive. This method, however, proved to be only marginally more effective than the press fit alone. Thus it was observed that the bond strength of the photopolymer on the monofilament fiber was poor. For assemblies requiring higher tension forces, an alternative adhesive would be required to provide adequate fixation.

5. CLOSURE AND FUTURE WORK

The authors present in this paper a method for creating actuated assemblies using the Objet PolyJet 3DP process. Taking advantage of the technology’s ability to create parts with both rigid and flexible materials, the authors propose a technqiue wherein fibers are embedded into the assembly to serve as ligaments that can be actuated.

The process begins with the design of both the part and the channel into which the fiber will be embedded, with careful consideration given to the required clearances of the fiber and the channel. The second step in the process is to pause the build process at the proper layer (with the aid of a pause indicator built from a unique material) and clear the support material from the channels. The fiber is then embedded into the part and secured by depositing liquid photopolymer resin and exposing the area to UV light at the proper wavelength to cure the material. Finally, the build is resumed and allowed to finish normally.

This process has been validated with two successful case studies that both achieved actuation with living hinge joints as well as revolute joints. However, we recognize that there are limitations in the current method. One limitation is that this method is only viable for a planer fiber path, and also requires that multiple fibers embedded into the same part lie in parallel planes. A second limitation is that a skilled operator is required to not only pause the build, but to clean the channels, manually embed the fiber, and bond the fiber to the part.

Possible further work would be to assess the viability of shape memory alloy (SMA) as an implantable actuator. The use of SMA may be limited due to the poor heat resistance of the photopolymer material used in the Objet PolyJet process. Furthermore at this point, the embedding of an object larger than a filament of 0.015 inch width has not been attempted. Further work into embedding of larger objects will serve to define the boundaries of this approach. The current ability to embed fibers allows for basic circuits to be formed by substituting conductive material for the fiber used previously; however, embedding of electrical components that would be needed to complete the circuit is an as of yet unexplored part of this technology. The embedding of electrical components and circuits, as well as piezoelectric material, combined with the multi-material capability of the process, could lead to the additive manufacture of energy harvesting devices.

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