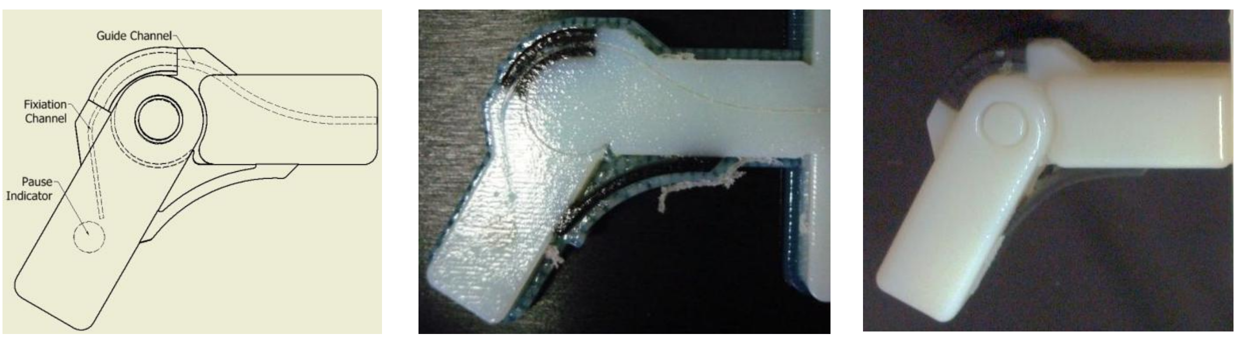
A monofilament strand, with circular profile and a diameter of 0.015 inch, was chosen for embedding. Fixation channels were placed at the tip of the finger and in the slider. The channels had a width of 0.015 inch and a depth of 0.020 inch, resulting in a zero clearance fit. Guide channels were used 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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