4D Printed Structures to mimick human hand joints

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Abstract—4D printing is a brand-new concept in the area of 3D printing, 3D printed structures will change physically or chemically when provided with the correct stimulus. This research investigates the effect of different designs and heat on the deployability of joints in 3D printed structures using the Shape Memory Effect (adding the 4D aspect). The investigation was supported by recent and relevant advancements in this narrow field. A 3D printed object embedded with elastic is used as a tool to explore the concept of 4D printing. From that a sequence of jointed designs were developed and manufactured to enable the final design to be developed. Using temperature as a stimulus the thermal properties of readily available Finally, a 4D gripper was designed and manufactured as a proof of concept.

Keywords—4D printing, PLA, deployable structure, thermal stimuli

I. Introduction

The cutting edge sector of 3D printing now is 4D printing, a term coined by a research group at MIT. In a review of 4D printing, Pei [1] states "4D printing as the process of building a physical object using appropriate additive manufacturing technology, laying down successive layers of stimuli-responsive composite or multi-material with varying properties. After being built, the object reacts to stimuli from the natural environment or through human intervention, resulting in a physical or chemical change of state through time". An example would be to print a flat net that, once exposed to a stimulus, transforms into a cube. To have 4D printing there must be; a 3D printer, or a variation of it laying down material successively or fusing particles/curing resins, a stimulus/stimuli and a single material or multiple materials to print with. Very little published research has been done on 4D printing even though production grade thermoplastics are already commercially available [2].

Almost every material will change its chemical or physical properties in response to a heat source. This ability to change shape can be used for motion or force generation. The shape change effect (SCE) is where material responds to a stimulus in an elastic or visco-elastic manner e.g. melting and cooling. In contrast the phenomenon of shape memory effect (SME) occurs when the deformed shape is maintained indefinitely until the same stimulus is applied again as a driving force to trigger the recovery to its original shape [3].

The glass transition temperature (Tg) is linked to the SME. Below Tg a material is hard and brittle and above it, viscous and rubbery. Shape memory polymers (polymers that exhibit the SME) take advantage of this effect when recovering their shape. When heated above Tg the material is viscous. An external load applied causes internal stresses, deforming the shape. When cooled below Tg it becomes hard, locking the internal stresses in place. This is the temporary shape.

Poly(lactic acid) (PLA) has an excellent heat responsive SME when exposed to temperatures above its Tg (about 65°C), at room temperature it is brittle [4]. For example PLA recovery in the SME is fully repeatable below 90°C. Above this (i.e. boiling water) the heat induces crystallization, so the PLA once in its temporary shape will not recover. This could be a useful effect if a different "original shape" is planned.

4D printing can be applied to practical solutions such as: a 3D printed window blind that opens to shade the home when the sun is up and closes automatically [1] or compacting a 3D object into a flat one [5] saving space and money for shipping. The compact object could then be deployed when at its destination, this could even reduce overall manufacturing costs with self-assembly. Other applications could be the development of drug delivery systems, adaptive water pipes that expand with high-pressure, hot and cold water valves and many other opportunities will, no doubt, appear when the techniques of 4D printing are refined.

The aim of this work was to design a working 4D printed structure of a human hand using commercially available 3D printing filament for the manufacture. The hand should close around a cylindrical object, grip and be able to lift it without the object sliding, demonstrating a custom grip. The device should simulate a hand with the grip of fingers and a thumb. This grip will be driven by the shape memory effect.

II. Materials and Methods

PLA (2.85mm and 1.75mm diameter), ABS and PVA (2.85mm diameter) filaments were purchased by Ultimaker, while NinjaFelx™ (2.85mm diameter) was purchased by Fenner Drives company. The CAD models were created in Autodesk Inventor. Cura™ (created by Ultimaker) was the slicing software of choice, slicing software converts the 3D CAD model to specific instructions for the 3D printer. The 3D printed structures were manufactured by using the commercial 3D printers Ultimaker 2 and 3 available at Newcastle University. The materials test was created to discover the shape memory effect when using different materials within a range of thicknesses. The test pieces were printed in 0.5,1,2,3,4,5 and 6 mm thick pieces. The PLA and ABS were printed the Ultimaker 3 while the Ninjaflex™ by using the Ultimaker 2. The test pieces were first submerged in 70°C water and left there for 30 seconds.

III. Results and Discussion

The test pieces were first submerged in 70°C water and left there for 30 seconds. They were then removed from the water and bent to form a right angle. The bent test pieces were then re-submerged into the 70°C water and the angle through which they recovered was measured using a protractor underneath the water bath (c). This experiment observed the shape change from a 90° bent piece to flat piece (b). Similar experiments were performed by Wu et al.[6], where they looked at recovery ratio.

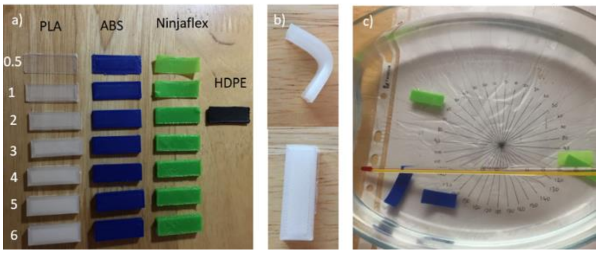

Fig. 1 a) CAD of 90°-90° b) CAD of 45°-45° c) CAD of PLA tendons d) Printed tendons e(and g) Printed, assembled 90°-90° and 45°-45° respectively f) 90°-90° after test; 45°-45° h) in temporary shape and i) effect with the temperature.

Different structures were investigated in order to evaluate their response to the temperature. Figure 2 shows the 3D printed structure simulating the joint, composed of three sections to the digit to better mimic a finger. The system relied on a channel to facilitate the introduction of the SME, PLA Tendon (a). Covers for each section were designed to be screwed onto the top covering the open face of the ABS skeleton to contain the PLA. The advantage of this system was that the PLA could be inserted in the printed position. Two digits were printed, one with two 45° angles (d) and one with two 90° (b).

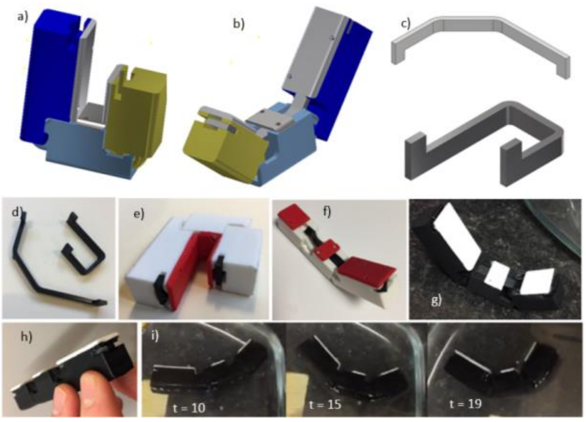

Fig. 2 a) CAD of 90°-90° b) CAD of 45°-45° c) CAD of PLA tendons d) Printed tendons e(and g) Printed, assembled 90°-90° and 45°-45° respectively f) 90°-90° after test; 45°-45° h) in temporary shape and i) effect with the temperature.

Having successfully achieved movement in one digit, the next stage was to design a basic hand prototype. The joints were designed to be fixed with simple pins. This was printed flat (**Error! Reference source not found.**Figure 3), thus saving printing time, but assumed a 3D shape when required (b). The hand was designed to grip a cylindrical object 0.5 the scale of a can (c). This design would be adapted to accept the PLA tendon.

A final design progressed into a life size "Gripper" Figure 4) that could be used to grip a can (a). This had six skeletal components, the hinges held together with robust pins. The PLA was bent round the outside of the arc formed by the gripper. Previously the PLA tendon was arranged around the inside of the arc. This was done to facilitate the drafting of the can itself in CAD. Other design elements included: the open-faced ABS skeleton was covered by sliding covers allowing the PLA to be placed and removed when needed. The PLA was held at both ends with slots created by the sliding covers, and some ABS protruded from the third segment to act as a handle upon submersion. When the gripper was formed into the temporary (straight) shape the covers slid with the PLA, one of the segments cracked and the PLA would not lie flat. This may have happened because the channel was not deep enough for the PLA (b). When the gripper was re-submerged into the 70° water it would not recover its original shape. This may be due to friction at the pin joints, trouble with PLA alignment to the joints, the PLA may not have enough force to pull the gripper to our curled position or having PLA on the outside does not facilitate movement (c).

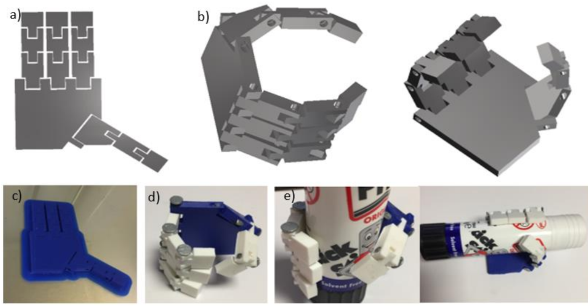

Fig. 3 a) Mini Hand a) CAD flat b) CAD posed for grip c) hand on print bed d) assembled hand e) demonstration of grip.

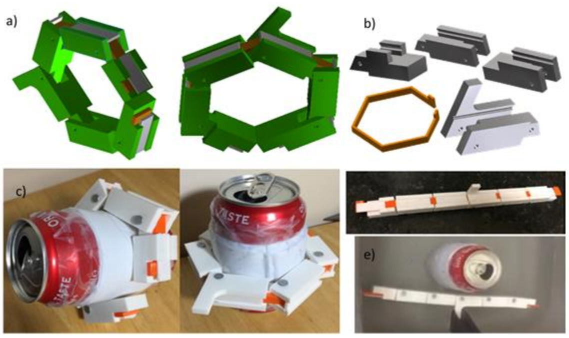

Fig. 4. Gripper 1 a) CAD assembly b) CAD components c) demonstration of grip d) temporary shape e) testing the Gripper1

IV. CONCLUSION

Different designs and heat on the deployability of joints in 3D printed structures using the Shape Memory Effect (adding the 4D aspect).

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