PRELIMINARY INVESTIGATION OF 4D PRINTING TECHNOLOGY FOR DEPLOYABLE UAV DEVELOPMENT

J. E. M. TEOH, C. K. CHUA, Y. LIU, J. AN, Y. LI

Singapore Centre for 3D Printing, School of Mechanical & Aerospace Engineering, Nanyang Technological University, Singapore

ABSTRACT: Current unmanned aerial vehicles (UAVs) are large in size due to fixed wings and mechanical components. 4D printing is a technology that allows shape transformation (e.g. compaction, extension) of a 3D printed object. In this research, we investigated the feasibility of using 4D printing technology to design and fabricate compactable structures for deployable UAV model. The investigation has also shown that the folding angles (0°, 15°, 30° and 60°) of the hinge for the back wing of UAV model is programmable and controllable. Additionally, the folding sequence of different parts of the wing is programmable as well by using multiple materials. We have also demonstrated that by integrating these basic programmable structures, a 4D printed UAV model can be compacted and then deployed upon thermal stimulation. Future works will address the scalability issue and detailed thermomechanical stimulation methods.

KEYWORDS: Four dimensional printing, rapid prototyping, additive manufacturing, shape memory polymer, unmanned aerial vehicle.

INTRODUCTION

Recent developments in 3D printing technology have provided the opportunity to print multiple materials in a single print (Chua & Leong, 2015; Lipson & Kurman, 2013). These new technologies allow users to print materials with varying programmed properties into various sections of the geometric design within the structure (Doubrovski et al., 2015). Such available printing materials include active materials, which can be activated by environmental stimulus to deform or reconfigure its structure. Shape memory polymers and shape memory alloys are examples of active materials (Hayashi, 1992; Zhao, Qi, & Xie, 2015). Applying active materials to multi-material 3D printing, a new form of printing – 4D printing, emerges (Khoo et al., 2015). In 4D printing, besides the regular three dimensions, the fourth dimension is time-dependent shape change of the printed product. We have fabricated 1D SMP structure using the PolyJet printer and the full recovery of the sample is demonstrated in Figure 1. The 1D sample would transform into the letters "NTU" upon heating. With 4D printing, models can now be printed in a specific form and activated by external stimulus to change its shape in a controlled manner (Ge, Dunn, Qi, & Dunn, 2014; Pei, 2014; Tibbits, 2014). Such ability facilitates the possibly of self-assembling features in designs, where printed products can interchange between a compact and assembled form. This can be done by designing folding patterns at specific locations that can be activated in sequence (Yu, Ritchie, Mao, Dunn, & Qi, 2015), providing the final assembled form of the structure.

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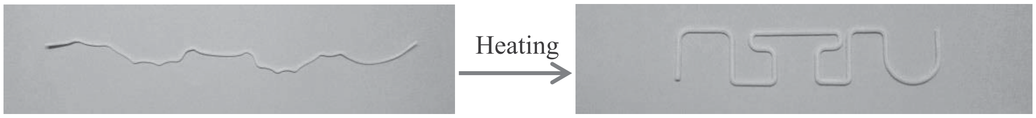

Figure 1. Printed sample of NTU before heating (left) and after heating (right)

Current unmanned aerial vehicles (UAVs) are large in size due to fixed wings and mechanical components. To design and fabricate compactable structures for deployable UAV, this paper describes the preliminary investigation of 4D printing methodology in physical simulation of UAV model (i.e. compaction and opening of wings). The 4D printing methodology implemented in this research comprises of shape memory polymer selection, 3D geometric design, 3D printing using Polyjet, 3D geometric programming and shape memory activation using thermal activation (Kamila, 2013). Single-axis or hinge design and analysis were performed to establish fundamental parameters for shape control. The fundamental parameters were applied in implementation of an UAV model comprising of multiple axes or hinges and complex shape change has been achieved successfully. The objective of this research is to establish the design methodology of self-response 3D printed structure (or known as 4D printing) through the use of thermally activated shape memory polymers (SMPs).

MATERIALS AND METHODS

Materials and equipment

Four different shape memory polymer materials (DM8510, DM8520, DM8530, VeroWhitePlus) from Stratasys were selected and a PolyJet printer (Connex 500) was used to fabricate the basic structures and UAV model.

Programming the Folding Angles of Hinges

A typical programming process for 4D printing is illustrated in Figure 2. A strand is printed using SMP materials with the Polyjet machine. To programme the strand, it is placed into the hot water, straightened and placed it in room temperature for it to cool. To achieve shape memory activation, the strand is placed into the hot water above the material Tg temperature and it will recover to its original shape (An, Teoh, Suntornnond, & Chua, 2015). Similarly, hinges of 90° were designed, printed and put into a heated water bathe and folded at different bending angles (0°, 15°, 30° and 60°) using different moulds. The hinges were pressed to the mould to form the angle before each was taken out of the water and cooled at room temperature. Each hinge was then at the fixed angle that was programmed.

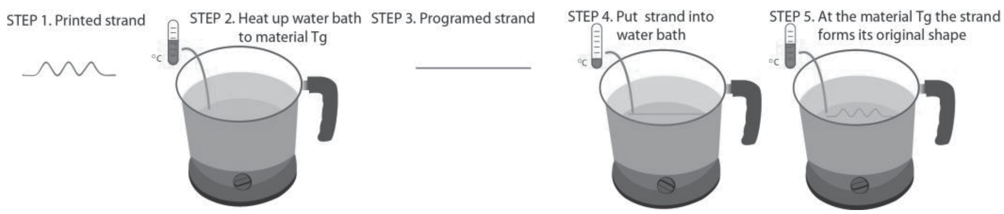

Figure 2. Programming process

Programming the Folding Sequence of Hinges

A multi-hinge square plate was designed, printed and put into a heated water bathe and four hinges at corners were manually opened. The plate was taken out of the water to room temperature to be programmed into a flat form. The flat plate was put into a water bathe above its Tg to achieve sequential folding.

Design and Fabrication of UAV Model

The UAV model has a dihedral angle of 170° between the wings. Each wing has a downward fold with bending angle of 150° at the front, while an upward fold with bending angle of 135° for the back flaps. These bends have been designed to have bending radius of 3mm. The thickness of the printed layer is 1mm throughout. Using the formula, Arc length = $\theta \cdot r$, where θ is the bending angle and r is the bending radius, the length of the hinge can be obtained. This is important as individual hinges are designed separately as they are printed in different materials.

Figure 3. UAV Front view (left), side view (right)

The UAV was designed to recover in 3 stages, hence the hinges have a variation of 3 different materials. The locations of the hinges are shown in Figure 4. Hinges 1a, 1b, 2a and 2b are the first to be activated to recover; hence they were printed in DM8530. Hinge 3 is second to be activated to recover and therefore was printed in DM8520. Hinges 4a and 4b are the last to recover, thus are printed in DM8510. The rest of the UAV was printed in VeroWhitePlus. To avoid interference and collision when recovering, hinges 1a and 1b will be folded in an opposite direction to hinge 3 in the temporary deformed state. Hinges 2a, 2b, 4a and 4b will be straightened so that front edge and the back flaps are in the same plane.

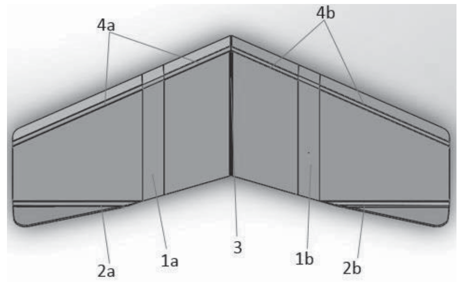

Figure 4. Hinge Location on UAV

Using CAD software, a 3D model of an UAV is drawn consisting of separate parts. Solidworks is then used to combine the separate parts into a component CAD file representing the UAV, so as to allow the application of different materials on each of the UAV part. Next, the CAD file is saved as .STL format before exporting to the Objet software. Using the Objet software, different materials are chosen for the different parts of the UAV, and the entire CAD model is printed using the Polyjet printer. Objet will first slice the 3D model of the UAV into many horizontal layers, each representing the cross-section of the UAV being sliced. Following which, Polyjet would print each layer of the UAV cross-section by dispensing the droplets of both the material ink as well as the support material. The layer-wise process would repeat until the entire 3D model of the UAV is printed.

RESULTS AND DISCUSSION

Control of Folding Angles of 90° Hinges

The programmed angle at 0°, 15°, 30° and 60° achieved 100% recovery to an original 90° angle (see Figure 5). Different percentages of materials were tested, which enables the structure to return to the printed angle.

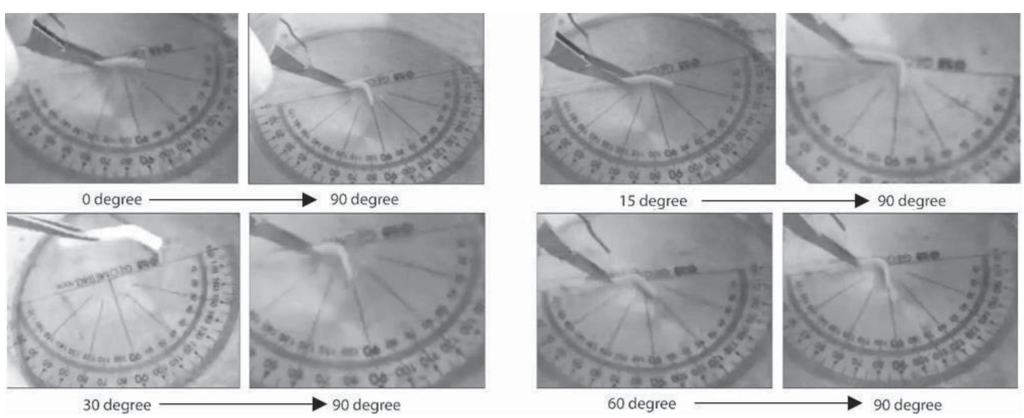

Figure 5. Programmable folding recovers to original 90 degree angle

Control of Folding Sequence of Hinges

Figure 6 shows controlled sequential folding process of a square sample with different materials printed at different hinge structures. However, only the hinges of the square sample were composed of SMP and the Tg temperatures for the various hinges were different. Hence, this causes the hinges to fold at different temperatures upon continuous heating with different rate of recovery, resulting in multi-stage folding of the sample as illustrated in Figure 6.

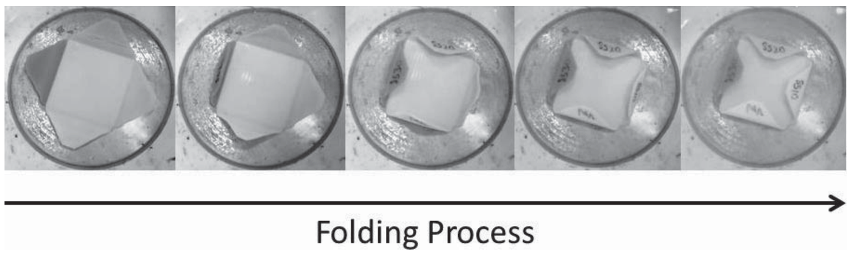

Figure 6. Multi-stage folding square with varying materials at different hinges

Compaction and Self-Deployment of UAV Model

The designed UAV model was printed as shown in 7. The blue sections contain similar material of same properties with the rest of the body, and are just of a different colouration. It has no significant impact of the folding sequence. After being left to RT, hinge 3 was heated in isolation by a metal rod at 80°C and folded. The isolated heating was necessary to facilitate easy isolated bending while avoiding recovery at the other hinges. Similar stages for hinge 3 were next carried out for hinges 1a and 1b. The folded UAV was then put in a room temperature water bath, which was subsequently heated. As the water temperature gradually rose, the sequence of activation of the folding recovery occurred as designed. The sequence is shown in the following figures (Figure 7).

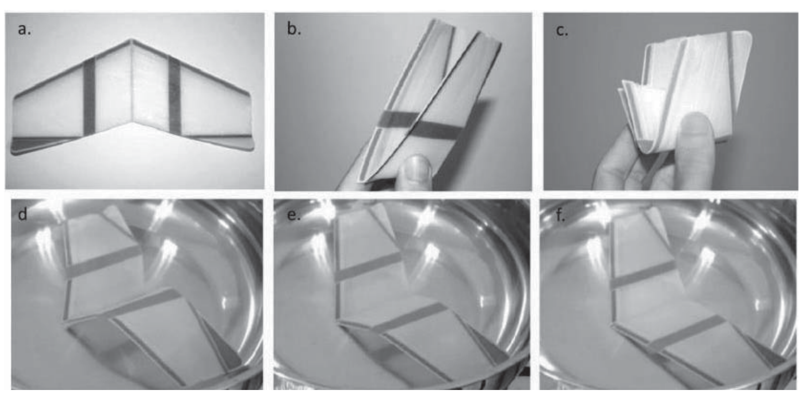

Figure 7. Programming UAV model and recovery of hinges 1a, 1b, 2a and 2b.

The preliminary application of reconfigurable multi-folding in a 3D object represented by a UAV model is exhibited in Figure 7. The multi-component parts are selected and the hinges are printed with shape memory materials. The heterogeneous materials are located specifically at the hinges such that the planar structure will not collide with the other areas during activation by thermal stimulus. As shown in Figure 7, the deployment of the UAV model unfolds consecutively from Figure 7d to Figure 7f when it is activated.

CONCLUSION AND FUTURE WORKS

Using the Polyjet equipment, we successfully fabricated a deployable UAV model consisting of shape memory polymer. Based on this research, it shows the feasibility of using 4D printing technology to fabricate a compact deployable structure. The sequence and folding angle can be controlled by thermal activation. Evaluation on design methodology for planar and hinge geometric change simultaneously created complex self-reconfigurable structures from 3D printed objects. Future research will be carried out for scalability and stimulation in a dry environment instead of a wet environment.

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