An Approach to Sequential Self-folding of Planar Sheet using Aluminium

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Abstract—Self-folding can transform a planar sheet into a 3-dimensional object autonomously. The application itself is an attractive feature in robotics, packaging, assembly and other fields but there are still challenges to achieve self-folding in a sequential manner especially when complex geometry is involved. This paper will introduce a simple approach to sequential and self-folding of a planar sheet with simple and complex geometry. The planar sheet is comprised of multiple layers of commercially available materials such as aluminium, thermo-responsive polymer sheet, paper and SMA. To achieve sequential self-folding, the multi-layer sheet is designed to utilize the differences between the thermal properties of the materials, the width of exposure to heat of the polymer sheet as well as the geometry design of the target structure. The integration of properties and the manipulation of parameters are keys to achieve a successful sequential self-folding of the multi-layer sheet to form a target 3D object.

I. INTRODUCTION

The art of paper folding, also commonly known as Origami, has existed for centuries and is popular among people of all ages across many fields, including the architectural and engineering field. Its popularity is mainly due to its conceptual fold design which encompasses simplicity and complexity together, as you can construct various shapes and create rigid structures that can support objects many times its weight with only a piece of paper or more. The simplest concept of origami is understood as the folding of a piece of paper multiple times to create a simple shape or a complex 3-dimensional object. In the mid-1970s, mathematicians discovered that an endless number of shapes could in theory be created using traditional origami which led to the incorporation of origami principles into new methods of manufacturing, assembling and morphing of devices and structures [1,2,18]. Thus, origami offers engineers novel approaches to fabricate, assemble, store and morph structures by providing them with advantageous features such as the capability to compactly store deployable structures (e.g. airbags), the structural capability to reconfigure and the reduction in manufacturing complexity [1]. In addition, folded designs have been applied in the fields of space exploration and logistics, and with the rapid improvement in technology, it will not take long for folded designs to expand into other fields [1,3].

Recently, origami-inspired folding has been fabricated at millimeter to centimeter scale robotics but fold actuations are still challenging because these types of robots require prolonged assembly and microsurgeon dexterity to be manually assembled [4,5]. Moreover, well-defined folds in self-folding sheet robots can be difficult to achieve especially those with complex geometry design. For a sheet with non-zero thickness, a fold is defined as any deformation of the sheet that preserves a continuous neutral surface, i.e. a surface that neither stretches nor contracts, and prevents self-intersection. Bending is an essential deformation in origami folding [14]. The challenges of a self-folding origami robot are (1) achieving a bilateral direction of self-folding, (2) performing a sharp bending angle of up to 180°, and (3) performing sequential and multiple bending at the same point of the sheet [12]. Numerous self-folding mechanisms and approaches have been developed and studied such as folding lithographically patterned thin films spontaneously via residual stress [6], folding hydrogel composites with differential swelling via water exposure [7], folding layered composites via changes in pH, temperature or addition of solvent [4,17], and more [9-11,19]. A recent study uses printing technology to induce self-folding of a paper robot with a printed electrothermal actuator [20] or with varying aqueous solutions [21]. Another recent work utilizes selective light absorption to allow inexpensive, single-use shape memory polymers (SMPs) to self-fold into target structures [8]. The self-folding approach of using SMP is simple and inexpensive but it is difficult to achieve well-defined fold lines such as sharp edges by using only SMP.

The objective of this paper is to propose a novel approach to sequential and self-folding of a planar sheet by incorporating multiple layers of aluminium, thermo-responsive polymer sheet (SMP) with thickness of 2 mm, paper and SMA (shape memory alloy). This approach focuses on a few main points to achieve sequential self-folding which are: (1) using cheap and commercially available materials, (2) utilising the differences in thermal properties of each material and (3) modifying the design depending on the geometry of target structure.

II. DESIGN FORMULATION

A. Design Approach

The aim of the multi-layers is to introduce a simple approach to the self-folding of the sheet. By multi-layering the materials into 1 sheet, each material serves a different function complementary to the other layers to facilitate folding. The
The disadvantage of multi-layering is that it will increase the total thickness of the sheet and may compromise the folding angle. The sequence of self-folding may be achieved by manipulating the number of material layers, the type of materials used and the width $W$ of ‘hinge’ or heat exposure. Thus, the important features of this multi-layer design are (1) differential thermal properties of the materials to control heat transfer, (2) using shrinkage as a pulling force for bending/folding motion, and (3) changing the width of ‘hinge’ to control timing sequence of folding. The following factors are also taken into consideration in the outline design of each material layer: (1) direction of folding in the $z$-axis, (2) thermal properties of material, (3) timing of each deformation/folding, and (4) geometry design of target 3D shape.

For example, given a rectangular planar sheet with 1 mountain crease (red line) and 1 valley crease (blue line) which are parallel to each other and the anticipated folding sequence starts with the mountain fold and then the valley fold, the general design of the multilayer sheet will be as illustrated in Fig. 1.

In Fig. 1, $A_1$ is defined as the surface area with width $W_1$ that is not covered by an aluminium layer and hence, allows heat localization at $A_1$. The same principle is applied to $A_2$ with $W_2$. As shown in Fig. 1(b), the width of heat exposure $W_1$ is larger than $W_2$ and the total number of layers along the $z$-axis is 5. This 5 multi-layer sheet consists of a layer of aluminium, paper, polymer sheet, paper and aluminium arranged consecutively from top to bottom. When this multi-layer sheet is heated in the oven, the regions $A_1$ and $A_2$ get heated faster than the regions covered by the aluminium layer. Thus, heat becomes localized at $A_1$ and $A_2$ and the temperature of the polymer sheet at these exposed regions increases faster, creating a temperature gradient. As the temperature increases towards the glass transition temperature $T_g$, viscoelastic strain relaxation occurs at these regions. Then the polymer sheet undergoes shrinkage and folding is induced. The rate of heat transfer at region $A_1$ is faster than at the region $A_2$ and hence, folding occurs at $A_1$ first followed by folding at $A_2$ next. Thus, the sequence of self-folding can be manipulated by varying the width of heat exposure $W$.

### B. Self-folding Mechanism

To create a valley fold, the arrangement of the material layers is shown in Fig. 2(b) with 4 layers consisting of aluminium, polymer sheet, origami paper and aluminium arranged consecutively from top to bottom. Conversely, to create a mountain fold, reverse the arrangement of materials where the paper is placed at the top of the polymer sheet instead of at the bottom. The aluminium layer acts like a clamp, restricting the boundaries that it covers and thus, creates a free boundary to allow thermal folding response within the hinge/folding region as illustrated in Fig. 2(a)-(b). Aluminium also acts as a heat insulator, preventing heat transfer to the polymer sheet underneath it, facilitating the indirect localization of heat to the hinge/folding region. In Fig. 2(c), $L_{poly}$ indicates the length of the polymer sheet within the hinge region while $L_{paper}$ indicates the length of the paper within the hinge region. The initial length of $L_{poly}$ and $L_{paper}$ correspond to the width of heat exposure $W$. Thickness $t_{poly}$ indicates the thickness of the polymer sheet while $t_{paper}$ indicates the thickness of the paper origami.

![Fig. 1](image1.png)

![Fig. 2](image2.png)
III. EXPERIMENT

A. Experimental Setup

The objective of the experiment is to achieve sequential self-folding of the multilayer sheet to form a 3D object through the manipulation of the sheet design. The experiment is designed to follow the step by step achievements of sequential self-folding corresponding to the expected pattern sequence. The sheet design is based on the geometrical folds of the assumed 3D shape and its pattern sequence of folding. The following experiment is designed based on the geometrical folds of a simple ‘Penguin’ origami illustrated in Fig. 3 and its expected sequence of folding as illustrated in Fig. 4. The sheet will be heated in an oven at 135°C with top and bottom heating (including fan for circulation). The total multi-layer sheet size dimensions used in the experiments is 150 mm by 150 mm.

Fig. 3 Penguin geometry design (red: mountain, blue: valley) where the geometry of ‘head’ of penguin is situated at the top left, the ‘wing’ at the sides and the ‘tail’ at the bottom right.

Fig. 4 Flowchart of expected sequence of the folding of penguin origami

B. Sheet Design

The design of each material layer in the sheet is dependent on the type and number of folds of the target shape.

Cross-fold and Diagonal Geometry

In this experiment, cross-fold (cited as the ‘tail’ in Fig. 3) is defined as the intersection of 2 crease lines consisting of mountains and valleys. The geometry itself may seem simple at a glance but it consists of 2 valleys and 1 mountain joined at a single vertex. A successful cross-fold occurs only with the correct sequence of folding. The cross-fold will not be in a complete folded state if the direction of folding changes (i.e. the role of mountain and valley reverses and thereby changes the intended geometry design) and if the folding motion goes against the expected folding sequence. A diagonal fold is defined as the crease line representing the ‘wing’ part of the origami.

The final multi-layer sheet consists of a layer of polymer sheet, 2 layers of paper origami and 2 layers of aluminium. The outlines of each material layer are shown in Fig 5. The arrangement of the layers from the top to bottom is aluminium, paper origami (top), polymer sheet, paper origami (bottom) and aluminium, where all are aligned at the correct orientation. A square hole is cut at where the vertex lies on the polymer sheet.

Fig. 5 Cross-fold and Diagonal Geometry outlines (a) Outline of polymer sheet with a square hole at the vertex (blue line: valley, red line: mountain) (b) Outline of aluminium (symmetrical on both sides) with width of exposure W₁, W₂ and W₃ (c) Outline of paper origami (bottom) (d) Outline of paper origami (top)

Complex Geometry (Head)

In this experiment, complex geometry fold is defined as the complex geometry of the head consisting of multiple vertices interconnected by multiple mountains and valleys (represented as ‘head’ in Fig. 3). Due to the abstract geometry design of the head and its folding motion, it is expected that the use of polymer sheet may be insufficient to aid the extensive multi-directional folding motions of the head. The folding of the head requires the dihedral angle of the wings to be $0^\circ$ prior to the folding of the head. Thus, the multi-layer design outline is simplified and modified to exclude the folding of the wings in the folding sequence (which then omits the aforementioned requirement factor) as illustrated in Fig. 6.1 and Fig. 6.2. The
multi-layer sheet then consists of an additional SMA, 1-2 layers of paper origami, 1 layer of polymer sheet and 2 layers of aluminium. In Fig. 6.1, the arrangement of the layers from top to bottom are aluminium, polymer sheet, aluminium, paper origami and SMA. While in Fig. 6.2, the arrangement of the layers from top to bottom are aluminium, paper origami (top), polymer sheet, aluminium, paper origami (bottom) and SMA. For both figures, the wings part of the origami will be folded along the mountain creases and the edges will be taped to the body. Both the sequence and direction of folding are important to achieve the target 3D structure.

Fig. 6.1 Complex Geometry (Head) and middle fold (a) Outline of paper origami with SMA wire (blue line) attached at bottom side (b) Outline and location of polymer sheet (c) Outline of aluminium (shaded area; symmetrical on both sides)

Fig. 6.2 Complex Geometry (Head) and Cross-fold (a) Outline of bottom paper origami with SMA wire (light blue) attached at bottom side (b) Outline of top paper origami (c) Outline and location of polymer sheet (d) Outline of aluminium (shaded area; symmetrical on both sides)

C. Results and Discussion

On observation of the cross-fold and diagonal geometry experiment, the onset of deformation starts earlier when the width of heat exposure is larger. Smaller width (e.g. width $W_2$ is smaller than $W_1$ and $W_3$) allows folding (of the wings) at a later time. The duration to complete deformation may be correlated with the area of exposure to heat. As the area of exposure to heat increases, the duration to complete deformation prolongs due to heat transfer and temperature gradient. The angle of deformation is larger when the duration to complete deformation is shorter. This may be due to the basis that rapid strain relaxation from large strains leads to rapid folding of polymer and hence, bigger angle of deformation. By manipulating the width of exposure $W$ and the area of exposure to heat $A$, the sequence of self-folding resulted in the expected folding sequence shown in Fig. 7. In the following experiment, the formation of the 3D penguin origami is asymmetrical and the folding motions are insufficient. The shrinkage of the polymer sheet is asymmetrical which may be due to non-uniform heating and other factors. The sequence of self-folding starts with the initial deformation of the head, followed by the body and finally the complete folding of the head. Sequential self-folding is achieved but the results of folding motions are unsatisfactory.

In the design of the multi-layer sheet, the difference in the thermal properties of the materials is an important factor to control heat localization and thus heat transfer to the polymer sheet. By increasing the width of heat exposure $W$ and thereby, increasing the surface area of heat exposure, temperature gradient is generated across the thickness of the polymer sheet at a faster rate. Subsequently, the polymer sheet undergoes rapid shrinkage and the onset of deformation becomes earlier. Varying the width of heat exposure at different crease folds can therefore vary the sequence of folding. Additionally, the duration to complete the deformation of a crease fold can be determined by the surface area exposed to heat $A$. Larger surface area exposed to heat leads to a longer duration to complete deformation. Consequently, both width $W$ and surface area $A$ can be varied to manipulate the timing and duration of the folding sequence of the sheet.

However, there were several issues that occurred during the experiments. The uniformity of heat distribution to the multi-layer sheet through convection was difficult to control leading to non-uniform heating. Thus, certain parts of the sheet get heated faster than other parts leading to a disruption to the flow of expected sequence of self-folding and the direction of folding. For example, the folding sequence changes as one (or more) fold gets heated first prior to its turn. This may or may not affect the formation of the final 3D origami shape, but if certain important folding steps are skipped, especially in relation to complex geometry, the final 3D formation will fail. Also, non-uniform heating to one side of the polymer sheet (asymmetric heat transfer) can cause that side to heat faster and thus, asymmetric curling of the sheet towards the heat source. This can be a problem if the polymer sheet curls away from the intended direction of folding such as reversing the mountain fold with the valley fold, hence changing the geometry design and final 3D transformation shape.

Weight distribution of the multi-layer sheet is also an important factor to consider in the self-folding mechanism. If the sheet is too heavy, 3D transformation may be difficult. Particularly, the pulling force generated from shrinkage must be greater than the weight of the object that it is pulling. Otherwise, if the pulling force is equal to the weight, no fold/bending occurs, and the sheet remains on plane. If the pulling force is less than the weight, (that is, the weight of the object is greater than the pulling force), the direction of folding changes to the opposite direction and towards gravity. Subsequently, as the intended direction of folding changes, the final 3D transformation shape also changes.

Additionally, timing is another important factor in the flow of folding sequence. Timing includes the onset of deformation...
and the end of deformation. The onset of deformation of each fold must be timed accordingly so that none of the folds will precede the first fold, and this condition is applied to the next subsequent fold. For example, the tail must fold first before the middle body. Otherwise, if the middle body folds prior to the tail, a constraint is generated, and the folding of the tail becomes restricted. As discussed previously, the timing (and thereby the onset of deformation) may be controlled by varying the width of heat exposure $W$ and the surface area exposed to heat $A$.

However, varying the width $W$ and surface area $A$ may be insufficient to achieve sequential self-folding. As observed in Fig. 6.2, the shape outline of the polymer sheet is a pentagon with a cross-fold outline diagonally in the middle whereas the shape outline of the polymer sheet in Fig. 6.1 is a square shape with a cross-fold outline diagonally in the middle. Given that the width of heat exposure $W_1$ and $W_2$ are the same between both multi-layer sheets, the multi-layer sheet in Fig. 6.2 fails to create adequate folding motion as similarly demonstrated by the multi-layer sheet of Fig. 5 (cross-fold and diagonal geometry). One of the possible causes of the shrinkage variation is non-uniform heat distribution as discussed previously. Other potential causes of the shrinkage variation are the relationship between the outline shape of the polymer sheet, the angle of strain/shrinkage direction and the overall size dimensions of the polymer sheet. Further research and experiments are needed to determine the causal relationship of these factors with shrinkage control.

The formation of a space or gap between the layers outside the hinge/folding region (as indicated in Fig. 2) may contribute to the error in the folding motion as the folding mechanism changes with the addition of new variables and forces. Thus, it is important to ensure that the material layers within the constrained shaded region remains attached to each other throughout the transformation process.

IV. CONCLUSION AND FUTURE WORK

The modelling of the self-folding of polymer and the sequential feature is a difficult challenge as both temperature and strain change dynamically in a complex manner during folding. Essentially, self-folding is significantly affected by heat absorption and heat transfer, the non-linear relationship between temperature and shrinkage, and the conservation of mass in the hinge or folding region [13]. Additionally, there are other factors that need to be taken into consideration in the outline design of each material layer such as direction of folding in the $z$-axis, the thermal properties of the material used, the timing of each deformation/folding, and the geometry design of target 3D shape (including the types of crease folds). The sequence of self-folding can be achieved by manipulating the width of heat exposure (to promote heat localization) and the surface area exposed to heat, but the sequence of self-folding may also be affected by other variables such as (1) relationship between the shape of polymer sheet and the angle of strain direction, (2) size dimensions of polymer sheet, (3) symmetry of shrinkage, (4) weight distribution of the multi-layer sheet must be less than the shrinkage force, and (5) detachment layers within the constrained (shaded) region.
In conclusion, integration of properties and manipulation of parameters are keys to achieve a successful sequential self-folding of the multi-layer sheet to form 3D origami. Timing of deformation is important to determine the correct sequence of each folding steps as certain steps must be set prior to the next process. There are multiple variables that may affect the self-folding mechanism and the sequential folding that are not limited to the thermal properties of the polymer sheet and thus, further studies are required for this underactuated self-fold system. The geometry and outline design of each material layers may need to be revised for improvement of the multi-layer sheet’s performance. Moreover, the current design approach produced a unidirectional self-fold system as SMP is used and hence, this system can become non-ressilient if predispersed at high temperatures especially above 100°C prior to use.

For the future work to achieve sequential self-folding, the current approach may be improved by using a heat equipment that distributes heat more evenly and uniformly to the multi-layer sheet. However, the issue with heat distribution may be largely due to the design of the sheet and thus, the outline designs must be modified to minimize the shrinkage variations of the polymer sheet by perhaps minimizing the area or size of the polymer sheet exposed to heat. In addition, other substitutes or materials with different thermal properties such as thermal paste, cloth and others may be introduced into the layers to control the timing of self-folding. Further research and studies of the polymer sheet to achieve a folding angle of 180° are needed to acquire better control of the polymer sheet.

Currently, this simple multi-layer approach is designed in reference to the mountain/valley folds and geometry of the desired target 3D structure. Therefore, to utilize this system approach, knowledge of the geometry of a particular 3D structure and its mountain/valley lines (when in planar state) are required for the sheet design. This sequential self-folding approach is still in the early stages and further improvements especially on the design are required to improve the control of self-folding and the sequence. Potentially, sequential self-folding origami robot sheets may be used in the application of (1) toys, where traditional origami and modern technology are incorporated together to create a contemporary fusion, and (2) space exploration, where self-foldable sheets are much easier to be transported compared to 3D complex shaped objects as there is a weight limitation in bringing objects into space.

MATERIALS

In the experiments, we use biaxially pre-strained sheet with thickness 0.2 mm and of Polystyrene chemical composition which is commercially available in Japan. This polymer sheet or “Shrinky Dink”, biaxially shrinks when heated in the oven and becomes thicker and more rigid after shrinkage. The aluminium tape used has a total thickness of 0.1 mm with aluminium foil thickness of 0.05 mm. The SMA used is muscle wire Nitinol COM-11899 with diameter of 0.127 mm and shape recovery temperature of around 100°C. The paper is common origami paper with 150 mm by 150 mm size dimensions. The total size dimensions of the multi-layer sheet are 150 mm by 150 mm.

REFERENCES