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# DESIGN AND PRINTING OF ORIGAMI STRUCTURES WITH FUSED DEPOSITION MODELING

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**Abstract**— This paper introduces origami folding techniques to evolve from flat material to the additive manufactured application deployed state. The study aims to design various origami structures from different folding techniques, understand their underlying mechanisms, create physical models and simulations to demonstrate and compare their folding feasibility. Mountain and valley folds, and origami shapes, among other folding techniques have been identified. All this concept was applied in the design of the origami structure. To determine the structural abilities of the origami structure on folding, seven origami ideas were developed. The model was developed using CAD tools (SolidWorks, Oripa, and Origami Simulator). Three analyses on three folding ideas have demonstrated the outcomes of design deformation using strain analysis. The analysis revealed that the change in the strain at the fold shows a good safety value. The difference in strain values between the valley and mountain folds on folds with holes (maximum strain is 7.917E -03, maximum strain when folding occurs is 5.9387E -03) is lower than on folds without holes (maximum strain is 5.957E -03, maximum strain when folding occurs is 5.957E -03), proving that folds with holes in the centre point are stronger and safer. Lastly, an open source FDM 3D printer was used to print and validate the origami structure's viability on Polyethylene terephthalate glycol (PETG) material. The result demonstrates that a variety of foldable origami design can be printed and can withstand folding many times without fracture.

## I. Introduction

Additive manufacturing (AM) varies fundamentally from standard formative or subtractive production. AM is versatile, scalable, highly adjustable, and can suit most industrial development sectors. In AM, a great deal of work is needed to overcome the problems associated with its two main technologies, namely materials and metrology, to accomplish this capability in a predictive and reproductive manner [1]. AM is an apt name to characterize the innovations that create 3D structures by applying material layer-on-layer, whether plastic, metal, concrete, or human tissue is the material. The still-young technology will develop its full potential on a broad front and have the way for new products in many industries only when this leap is successful. For example, lightweight and vibration-damping engine mounts are of interest [2]. AM may contribute significantly to the realization of these specifications.

0rigami structures are typically created by folding a two-dimensional sheet that creates a certain crease pattern [3]. Origami, also known as paper folding, has shown the ability to create 3D structures on a flat sheet from designed crease patterns. Metamaterials inspired by origami were designed, tested mechanically, and modelled. When using a triangular-based crease pattern, one novel origami model was folded, and the other was folded using a rectangular-based crease pattern. Metamaterial sheets inspired by origami were made from polylactic acid using an FDM printer [4].

This paper introduces folding techniques from origami to evolve from flat material to the additive manufactured deployed state. A review of recent origami and kirigami techniques used for this purpose will be done to understand their underlying mechanisms and create physical models to demonstrate and compare their feasibility through FDM printers. Many current researchers [5,6,7,8] are interested in the FDM 3D printer as an excellent platform to produce products by using the additive manufacturing application.

## II. Background Study

### A. Fused Deposition Modeling (FDM)

Fused deposition modeling (FDM) technology is an AM method that constructs 3D forms by taking thermoplastic polymer content filaments and pushing them through a heated liquefier to be extruded onto a building platform via a small diameter nozzle. Technologies capable of processing metals include fused deposition modeling, electron beam melting, selective laser melting, laser engineered net shaping, and direct metal laser sintering [9]. Fused deposition modeling (FDM) is influenced by various parameters. The parameters have been categorized into two large categories: machine and material parameters. System parameters are those parameters that the operator of the 3D printer will define during the generation of G-code files on the slicing program [10]. On the other hand, the material parameters are the filament material features or compounds being extruded through the nozzle. Some of the machine parameters include the raster angle, printing speed, melt flow rate through the nozzle, temperature, layer thickness, infill density, build orientation, and airgap [11]. The printed parts' quality, consistency and efficiency depend on these parameters [12].

### B. Origami Structure and Folding Technique

Easy diagrams of basic folds like valley folds and mountain folds, creases, reverse folds, squash folds, and sinks have been applied to origami structures. There are also standards called bases used in different models, such as an intermediate stage in creating the flapping bird is a bird base. Additional bases are the preliminary base (square base), fish base, waterbomb base, and frog base. The allocation pattern is known as circle packing or polygon packing. A circle-packing figure can be computed for any uniaxial base of arbitrary complexity using optimization algorithms. A repetition of reverse folds could obtain the diamond pattern [13]. These are repeated inline instead of mirroring the reverse folds so that the main crease represents a zigzag line. Therefore, the folded pattern has a distinctive two-way zigzag corrugation. This helps the sequence in all directions to be extended and retracted. This skill was used by Miura to build solar sails for satellites packaged in a very compact way and to have the full extension until unfolded. The pattern is made up of symmetric trapezoids that form a tessellation of the herringbone.

A parallelogram folded onto its diagonal is the basis of this pattern. The sides are twisted up diagonally from a parallel location. A sequence of parallelograms, so folded, forms a twisted helical fold. When a thin-walled cylinder shell is compressed with distortion, a related buckling pattern shows up. Yoshimura and diagonal patterns are close to each other. It varies primarily because the diamond pattern's valley folds shape a polygonal plane line, while the valley folds of the diamond pattern form a helical polygonal line [13].

The valley fold is the most common origami technique. In origami, fold one edge to meet another edge. The arrow shows the lower edge to the opposite edge. This is folding in half, in other words. Folding an edge to hit a crease or an overlap of creases is equally possible. The exact position may be conspicuous and not clearly indicated, or tiny dots or circles may be indicated. It is certainly here that the corner folds to touch the middle. The goal point is just above the centre, indicating tiny dots at the arrow start and end. At the goal end, there can often only be one dot. Most origami diagrams show an overhead view, like a 2D architect plan [14].

Opposite of a valley fold is a mountain fold. The paper folds to the opposite side. This implies either keeping the paper in the air to allow the paper to fold beneath or merely flipping the paper over and treating it as a valley fold. Usually, this is simpler. Therefore, it is easier to fold the paper away from the body instead of against it.

### C. Origami Design Structure

Explorative sketches will assist in generating the origami design idea. The idea came from a single-vertex origami piece of paper with straight-line rays called creases emanating from a fold vertex placed in its interior or on its boundary [15]. The single-vertex origami flattening is always possible to reconfigure the creased paper from any configuration compatible to a flat, non-overlapping position, in such a way the paper is not torn, stretched, and, for rigid origami, not bent anywhere except along the given creases. Very little is known mathematically about rigid origami [16]. The classical origami literature is concerned mainly with characterizations of folded states and axiomatics for folding patterns. Equally interesting and important, but also very little studied, is the motion planning problem for origami, i.e., the design of reconfiguration trajectories. In particular, the non-self-intersecting foldability and reconfiguration of rigid origami have received very little attention, mainly because it is a very difficult problem.

Other designs came from Kawasaki theorem, spring, poly fold, parallelogram, and pyramid. Draw the crease pattern provide signposts on the way to a fold. In a crease pattern, it can see everything that is hidden in the folded work. Its 'crease pattern' is called to characterize an origami model only by representing the creases with several types on the unfolded flat piece of paper. The details found on the crease pattern are normally inadequate to explain the folded model with the full version. The evaluation of a crease pattern general ability to fold flat is a non-trivial issue. In comparison, if a crease pattern corresponds to a flat model, it does not guarantee its uniqueness. The crease pattern is similar (to a paper reverse dualization) and corresponds to two separate versions that can be defined as dual. A flat folded model needs only 6 radiating folds over 8, but that 8 folds retain a high symmetry in the models [17]. Figure 1 shows a crease pattern.

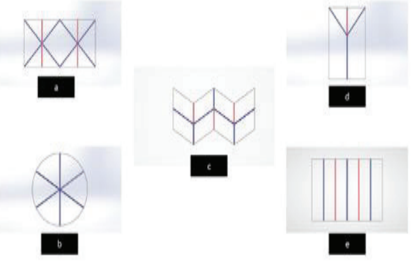

Figure 1: Example of origami crease pattern: (a) Kawasaki theorem, (b)circle fold, (c)Spring, (d)single vertex and (e) poly fold

## D. Material

A large range of usable FDM materials, fast material shift, low maintenance costs, simple production of thin components, total resistance equal to 0.1 mm, no hazardous materials, and very compact scale, operating at low temperatures, and so on [18]. As a general remedy for rough parts of acceptable strength, acrylonitrile butadiene styrene (ABS). Acrylonitrile butadiene styrene is short for ABS, and it is an amorphous polymer used in 3D printing. ABS is typically created from 3 elements or recycled from itself via the emulsion process. It's widely used in producing many everyday goods when pieces need more strength; ABS is used; however, some reinforced composites eventually begin to displace it. ABS's benefits are rigidity and toughness, recyclable, easy to post-process and paint, abrasive tolerance, higher temperatures of 212° F (around 100 ° C), many colours. and composites available can be machined [19].

PETG is practically indestructible in the layer direction due to its flexibility. Surface finishes improve when layer adhesion improves. It's a good choice for printing larger things because of its low shrinkage. Glycol-modified PET (PETG) is becoming increasingly popular because it is more durable than other filament materials. The addition of glycol prevents crystallization, so it won’t become brittle when heated. Glycol prevents crystallisation, which means it won't become brittle when heated [20].

## III. Methodology

### A. CAD Design and Simulation

CAD software is used to maximize designers' efficiency, enhance the quality of origami, improve communication of documents, and build a database for design. This research has utilized the ORIPA software to create the origami crease designs. It has a special attribute in that the folded form is determined from the pattern. This program used for identifying and measuring the folds that are designed. Figure 2 shows the ORIPA program. The origami structure design was designed and simulated with ORIPA. This software uses standard tessellation/triangulation language (stl) as a three-dimension file format that uses a series of triangles to explain a 3D model outer surfaces that to be 3D printed later.

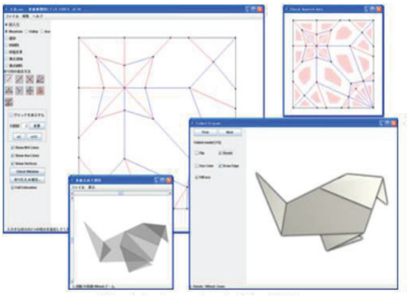

Figure 2: Oripa software is used to make fold lines and calculate the fold can be possible for this pattern

### B. Material Selection

This research used polyethylene terephthalate glycol, commonly known as PETG or PET-G, which is a thermoplastic polyester that provides significant chemical resistance, durability, and excellent formability for manufacturing to print the test specimen. PETG can be easily vacuumed and pressure-formed, and heat-bent thanks to its low forming temperatures. It is suitable for origami structure flexibility and stability.

### C. FDM Printing Process

The first stage in the 3D printing process is preparing a 3D model. 3D model creation can be done with 3D modeling software to help obtain the correct shape and size. 3D models that have been created are necessary to convert to stl (stereolithography) format. Stl format represents the shape of the 3D model and will become basic calculations when entering the slicing process. Stl files must go through a manipulation process, so later have the machine work setting information size, position, orientation, velocity, temperature, structure, etc. This process will generate a G Code file (gcode / .gco) to send to a 3D printer (via memory/wireless).

To begin the printing process, the printers must be prepared. Several processes must be done, including ensuring availability of power & backup power, set up the bed or work area (adhesive, flatness, etc.), and supply printed material for airtight packaging, filters. 3D printer work process takes place automatically, so it does not require continuous surveillance. Users only need to observe periodically to avoid material runs out, software errors, power outages, etc. Ensure that the 3D printer is neutral (motion, temperature/nozzle) so that the component does not damage and ruin the result. When extracting the part, ensure that the heat bed is cool to ensure that it does not melt. Using sharp-ended instruments (scrap) so that items will come off easily from the print base.

### D. Origami Sample Design

Most of the existing origami is used for paper folding, and the new era needs to have new materials for origami and technologies. This will also help designs from origami can be used in any application. Figure 3 shows the full sketches of the origami transform, which consist of several lines of the fold (valley and mountain). Each picture consists of a different type of origami structure. (a) shows concept 1, (b) shows concept 2, (c) shows concept 3, (d) shows concept 4, (e) shows concept 5, (f) shows concept 6, and (g) shows concept 7. This concept can be transformed and return to its original flat shape. The part consists of a valley line, mountain line, boundary line, and flat shape. However, the highlighted part is the line and thickness of material that can be able to fold properly without resistance and can return to its original shape, so the origami by using the FDM method can be achieved.


Figure 3: Design of seven concept origami

## IV. Result and Discussion

### A. Element of The Origami Design

There are a few elements that build up the origami design. Each element plays an important role and is essential in ensuring it can be used and function well as intended. The design is chosen according to the available crease pattern and based on the new idea. Concept 1 is a pyramid design fold. The four-line valley fold (blue line) is located on the flat structure guided by a pyramid design crease pattern. This mechanism is not suitable enough for the folding concept because of its thickness. So, technique welling of the layer is used as a line of valley folds. Figure 4 shows the design and element of concept 1.

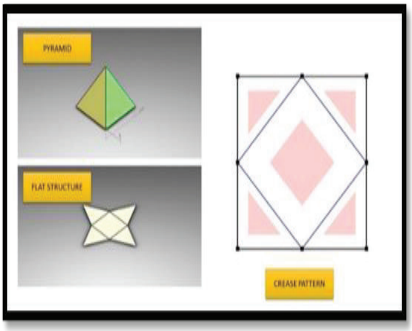


Figure 4: Pyramid Element.

Concept 2 is a circle fold design, as seen in Figure 5. The six-line valley fold (blue line) is located on the flat structure and has been guided by a circle fold design crease pattern. This mechanism is not suitable enough for the folding concept because of its thickness. So, technique welling of the layer is used as a line of valley folds.

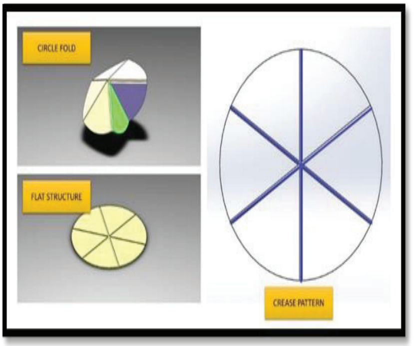


Figure 5: Circle Fold Element

Concept 3 is a poly-fold design. The three-line valley fold (blue line) and two-line mountain fold (red line) is located on the flat structure and have been guided by a poly fold design crease pattern. This mechanism is not suitable enough for the folding concept because of its thickness. So, technique welling of the layer is used as a line of valley folds and mountain folds. Figure 6 shows the design and element of concept 3.

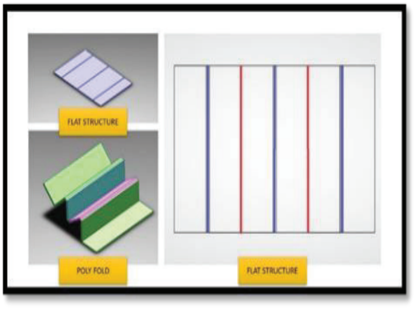


Figure 6: Poly Fold Element

Concept 4 is a single vertex design. The three-line valley fold (blue line) and one-line mountain fold (red line) are located on the flat structure and guided by a single vertex design crease pattern. This mechanism is not suitable enough for the folding concept because of its thickness. So, technique welling of the layer is used as a line of valley folds and mountain folds. A single vertex has three coordinates at one point, and this makes some problems occur when a folding process is at the centre point. A hole was added at the centre point between three lines (valley fold and mountain fold) as a solution. Figure 7 shows the design and element of concept 4.

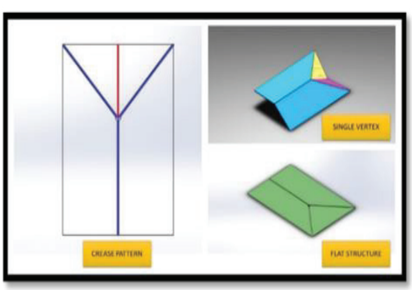


Figure 7: Single Vertex Element

Figure 8 shows the design and element of concept 5, which is a Kawasaki theorem fold design. The eight-line valley fold (blue line) and four-line mountain fold (red line) are located on the flat structure and have been guided by a Kawasaki theorem fold design crease pattern. This mechanism is not suitable enough for the folding concept because of its thickness. Technique welling of the layer is used as a line of valley folds and mountain folds. The Kawasaki theorem concept may be folded to form a flat figure. This design was upgraded to be the double design of the Kawasaki theorem.

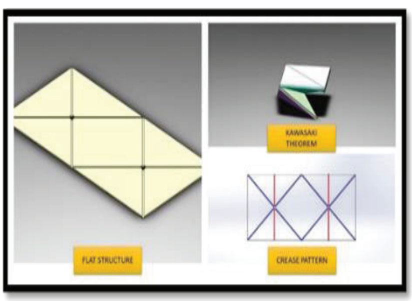


Figure 8: Kawasaki Theorem

Concept 6 is a spring element fold. The seven-line valley fold (blue line) and three-line mountain fold (red line) are located into the flat structure and have been guided by a spring design crease pattern. This mechanism is not suitable enough for the folding concept because of its thickness. So, technique welling of the layer is used as a line of valley folds and mountain folds. The top face is a valley fold, and the bottom face is a mountain fold. Added some holes at the centre point between three lines (valley fold and mountain fold). Figure 9 shows the design and element of concept 6.

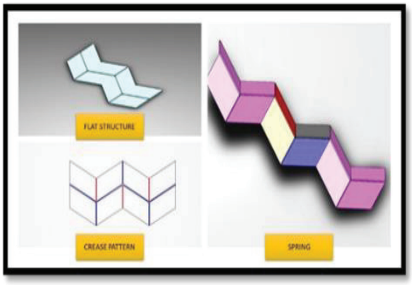


Figure 9: Spring Element

Figure 10 shows the design and element of concept 7, which is an origami chair design. The twelve-line valley fold (blue line) is located on the flat structure and has been guided by an origami chair fold design crease pattern. This mechanism is not suitable enough for the folding concept because of its thickness. So, technique welling of the layer is used as a line of valley folds. This design is very special because the origami structure can make several different views when see by side, front, or top.

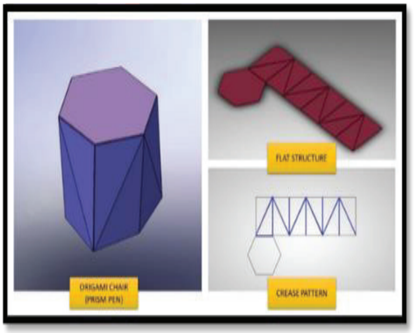


Figure 10: Origami chair

## B. Simulation Result

### i. Analysis 1

Solidworks simulation was used to know the ability to fold on potential and limitations of the origami design. All the samples were printed with polyethylene terephthalate glycol (PETG) material. An estimated 2N force similar to the force of the human natural hand fold was applied from the top and the bottom of the body. The centre of the body will become a fixed component. The analysis replicated the real situation when the user folds a printed origami sample. The strain result of the valley fold is shown in Table 1. The maximum value of the strain has been calculated as 2.684E -3. The maximum strain value when folding occurs is 2.013E -03. The minimum strain is 0. This indicates the folding current value is lower than the maximum strain value. This analysis shows that the design can be folded when folding occurs. Changing in strain value indicates elongation in the fold. This analysis also gives the positive result that this design is acceptable.

Table 1: Strain results analysis 1 (Valley Fold).

| Type Analysis: | Min | Max | Max (folding occur): |
|---|---|---|---|
| Strain-Test | 0 | 2.684E -03 | 2.013E -03 |

Figure 11 shows the simulation of the origami sample of the valley fold. The colour of the strain looks safe to do folds repeatedly.

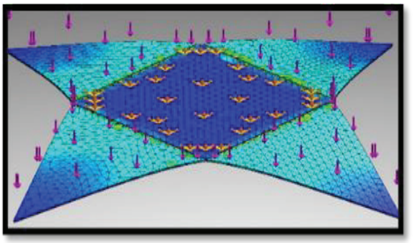

Figure 11: Analysis 1 Simulation (Valley Fold)

**ii. Analysis 2**

An estimated 2N force was applied from the top and the bottom of the body. The strain result of valley fold and mountain fold without a centre hole is shown in Table 2. The maximum value of the strain has been calculated as 5.957E -3. The maximum strain value when folding occurs is 5.957E -3 at the centre point between the valley fold and mountain fold. The minimum strain is 0. This analysis shows that the design can be folded when folding occurs, but the point of failure will be the cause of damage to the fold line, such as a fracture, or the fold does not reach its actual capabilities. Changing in strain value indicates elongation in the fold. This analysis gives a negative result, but this design is still acceptable.

Table 2: Strain results analysis 2 (valley fold and mountain fold without centre hole).

| Type Analysis: | Min: | Max: | Max (folding occur): |
|---|---|---|---|
| Strain-Test | 0 | 5.957E -03 | 5.957E -03 |

Figure 12 shows the simulation on the origami sample of valley fold and mountain fold without centre hole. The colour of the strain looks safe to do folds repeatedly.

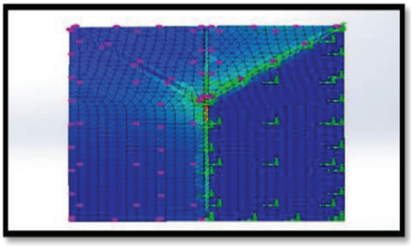

Figure 12: Analysis 2 simulation (valley fold and mountain fold without centre hole)

### i. Analysis 3

An estimated 2N force was applied from the top and the bottom of the body. The right side of the body will become a fixed component; this analysis replicated the real situation when the user is folding a printed origami sample. The strain result of valley fold and mountain fold with a centre hole is shown in Table 3. The maximum value of the strain has been calculated as 7.917E -3. The maximum strain value when folding occurs is 5.938E -03. The minimum strain is 0. This indicates the folding current value is lower than the maximum strain value. This analysis shows that the design can be folded. Changing in strain value indicates elongation in the fold. This analysis also gives the positive result that this design is acceptable.

Table 3: Strain results in analysis 3 (valley fold and mountain fold with centre hole).

| Type Analysis: | Min: | Max: | Max (foldin g occur): |
|---|---|---|---|
| Strain-Test | 0 | 7.917 E -03 | 5.938E -03 |

Figure 13 shows the simulation on the origami sample of valley fold and mountain fold with centre hole. The colour of the strain area is safe to be folded repeatedly after creating a hole at the centre point between the valley and mountain fold.

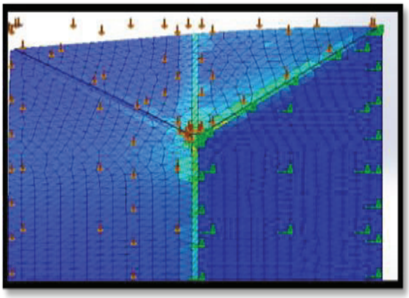

Figure 13: Analysis 3 simulation (valley fold and mountain fold with centre hole)

## C. Printed Origami Sample

Origami printed samples were successfully printed using a FDM printer with PETG filament material. Seven design concepts were successfully folded without damage and can be folded repeatedly. The folding structure looks like a chain thread that making origami strong and tough to break. The middle hole between the fold lines (valley and mountain) indicates the point of failure removed to overcome the collision between the lines during folding. Experiments were performed on origami that was printed. This proves the point of failure when folding is executed on origami that does not have a centre hole. A centre hole is required when the fold line meets another fold line. The thickness of the folds and the type of line structure for the folds are very important in making origami work well. Figure 14 shows the printed origami that was printed.

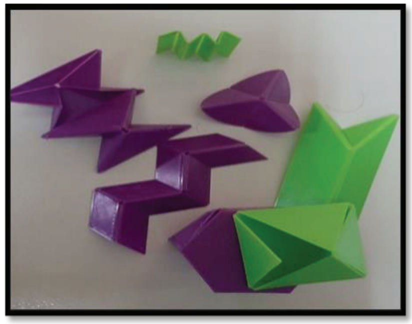

Figure 14: Seven concept of origami sample

## V. Conclusion

In conclusion, AM can be employed in origami design and development specifically the structure of origami and the issues that might arise during folding, such as origami thickness, which is a difficult issue in origami manufacturing. The basic idea of origami techniques, namely valley and mountain fold, was used to produce a variety of concepts when applying origami design and was successfully printed with PETG material due to its flexibility and stability characteristic. The creation of a design with a distinct structure and aesthetics, such as the seven concepts that have been developed. AM has proved to be a successful solution for origami design and development. The simulation analysis shows that it is important to understand the stress and strain distribution in the origami designs under compression loads. It showed the maximum strain appearing in the structure while folding occurred along crease lines. Depending on the fold angle and the design, the strain for these designs may be adjusted for specific engineering needs by changing the fold parameter. As a result of this research, origami will find more applications in the industry in the future.

## VI. Acknowledgement

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