Workshop

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19	Takashi Horiyama (Saitama University, Japan) "On the Enumeration and Counting of Developments of Polyhedra"
20	Tomoko Fuse (Independent, Japan) "Modeling by the infinite fold"
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22	Jun Mitani (University of Tsukuba, Japan) "Enumeration of formal crease patterns in the square/diagonal grid and verification of their flat-foldability"
23	Naoko Kishimoto (Setsunan University, Japan) "Folding Patterns and Deployment Processes in Morphological Changes of Insects"
24	Arzu Sorguc (Middle East Technical University, Turkey) "Origami Based Responsive System Proposal for a Building Surface"
25	Anna Lubiw (University of Waterloo, Canada) "Optimizing Unfoldings of Convex Polyhedra"
26	Jin-ichi Itoh (Kumamoto University, Japan) "Applications of cut locus and Intuitive geometry --continuous flattening of polyhedra"
27	Tomohiro Tachi (University of Tokyo, Japan) "Rigid Foldability and Self Foldability"
28	Naohiko Watanabe (National Institute of Technology, Gifu College, Japan) "Quaternion expression of the condition for rigid origami"
29	Yoshikazu Yamagishi (Ryukoku University, Japan) "Bifurcation diagram of disk packings on logarithmic spiral"

Superimposition of Rigid Origami Patterns

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1. Introduction

Origami-inspired engineering is used to apply origami science and technology to the design of engineering structures. The majority of existing self-folding structures either use a bespoke crease pattern to form a single structure, or a universal crease pattern capable of forming numerous structures with multiple folding steps.

2. Superimposition of Patterns

We propose a fundamentally new method, called *superimposition*, for generation of multiple 1-DOF rigid-foldable configurations from pre-defined crease patterns, such that kinematic independence and 1-DOF mobility of each individual pattern is preserved. Sheets can thus be created that contain multiple states with different or complementary functionality. The superimposed patterns can be classified into two families by considering the functionality, one is to fold the non-flat foldable patterns into a compact flat folding (Fig. 1), while the other is to fold the patterns in two steps to achieve much larger deployable ratio (Fig. 2). The proposed method has substantial potential for application in origami-inspired engineering design.

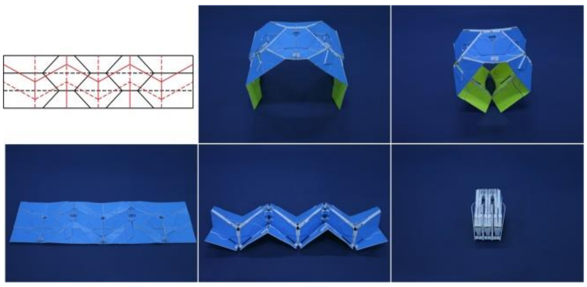

Figure 1 The thick-panel accordion shelter based on the superimposed Arc and Miura-ori patterns, with rigid motion between the two discrete states.

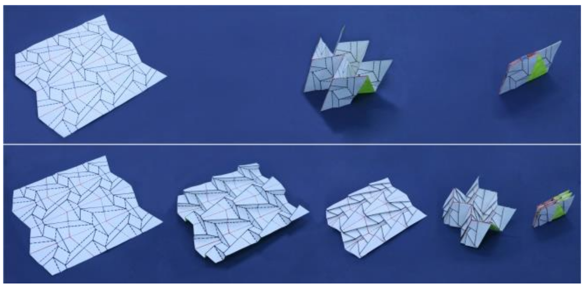

Figure 2 Two folding sequences of the superimposed pattern with different hill and valley crease assignment.

A Consideration on Industrialization of Origami Structure

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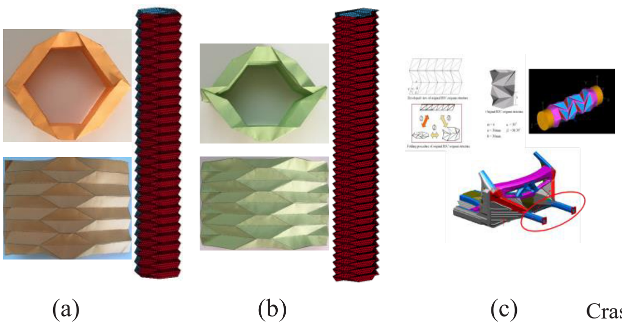
1. Introduction

Recently we have researched about pairing origami structures such as Nojima polyhedron and Tachi-Miura polyhedron for crash energy absorbers. They are both easy to be manufactured but not so much absorbed energy. On the other hand, reversed spiral cylindrical origami structure (RSC) has splendid ability for crash absorbed energy but it is difficult to be manufactured. These structures are shown in Fig.1. The RSC structure inspires us a new structure which has splendid crash absorbed energy and is easy to be manufactured. This is also the Origami engineering.

2. Force-Deformation Characteristics of Origami Structure and Its Application

Fig.2 shows that the initial peak force sometimes too large for passengers which is a representative Force-Deformation curve(F-D curve) for conventional hollow quadrilateral member. On the other hand, RSC has the ideal F-D curve parallel to the Deformation axis. We used origami structures for the helmet of "amazing skills" contest in the NHK which must be smaller than 300mm×150mm×50mm box and even if the weight 5kg from a height of 1m over the top has fallen in the head, the impact force must be damaged less than 10% without helmet. Our helmet consists of 3 origami structures shown in Fig.3. Fig.2 is the reason why RSC is selected among 3 parts. This contest is concerned with Origami engineering and crush problem which are both my measure. So we had complete victory. RSC anew inspired a splendid structure. And based on this helmet, the helmet on Fig.4 is on the market.



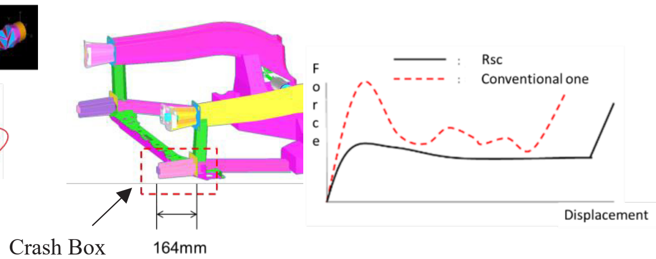


Fig.1 (a)Nojima Polyhedron ,(b)Tachi-Miura Polyhedron (c)Reversed Spiral Cylindrical Origami Structure

Fig.2 Crash Box(left) and Its load-displacement Characteristics(right)

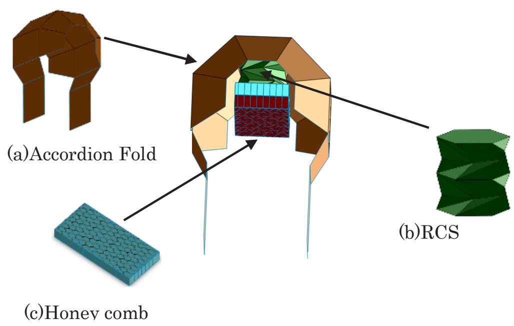


Fig.3 Origami-helmet for "Sugowaza" in NHK Television

Fig.4 Helmet on the market

Crease Patterns and Mechanisms in Insect Wing Folding

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Foldable hindwings in insects are one of the ultimate deployable structures and have large potential for engineering applications, because they have sufficient strength and stiffness to tolerate 20 – 1000 beats per second in the flight position, although they can be folded and unfolded instantly depending on the situation. Among wing folding insects, beetles (Coleoptera) are known to use the most highly diverse wing folding patterns and mechanisms [1]. Unlike six legs, the wings of insects are considered to be derived from the tergal exoskeleton. Their folding and unfolding mechanisms involve the elastic behaviors of structures, internal forces driven by muscle or blood pressure and external forces from other body parts. Understanding these mechanisms requires not only analyzing the materials and structures of the wings but also careful observations of how they are actuated in living specimens. This study focuses on a group of beetles that have elastic-deploying-type wings, and aims to reveal their wing-folding/unfolding mechanisms. These beetles use wing elasticity for deployments and therefore can quickly take off. On the other hand, when it comes to wing storing, they have to fold their wings against elastic forces. Usually, this process requires the supports of other body parts: the abdomen and elytra. Note that these folding movements can enable the beetles to achieve two different objectives at the same time: quick wing-folding and efficient storage of elastic energy for subsequent wing deployment. Therefore, detailed investigations of these movements are expected to generate useful knowledge in the development of excellent self-deploying systems. This study uses high-speed cameras to reveal the details of these motions. As a typical example of this type wings, this paper focuses on ladybird beetles (Coleoptera: Coccinellidae)(Fig. 1). First, on the basis of the reports of entomologists and our own observations, the factors relating to the actuation of insect wing folding and unfolding are described. Next the detailed motion involved during take-off and wing storing in ladybird beetles are observed using high-speed cameras. The analysis of these movies reveals the detailed processes of wing-unfolding and folding in ladybird beetles. Finally, the characteristics of wing-folding mechanism are summarized, and the potentials for engineering applications are discussed. The discussion also includes an outline of the future works required on the engineering side to reveal the detailed systems of these excellent deployable structures.

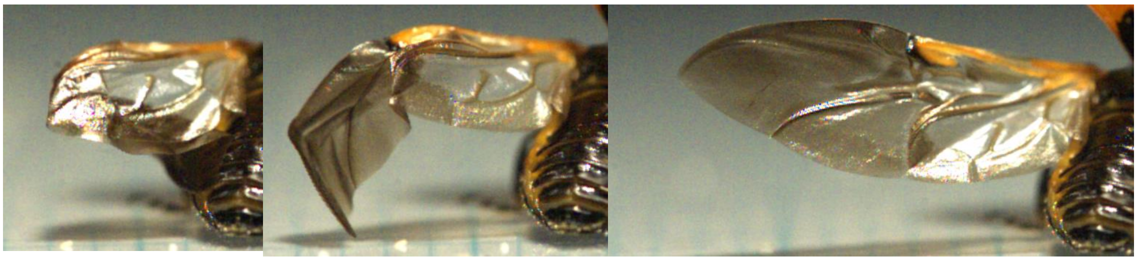

Fig. 1 Wing unfolding motion in a ladybird beetle

Reference

[1] Kazuya Saito, Shuhei Yamamoto, Munetoshi Maruyama, Yoji Okabe (2014) Asymmetric hindwing folding in rove beetles, Proc. Natl. Acad. Sci., 111(46), pp.16349-16352.

Characteristics of deformations on assembled structures by origami forming

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1. Introduction

Considering the earth environment and energy problem, the research as lightweight and high strength structures should be important. Assembled structures which can be produced by origami forming, have big merits on its application to improve the flexibility of structure designs. Characteristics of deformations of assembled structures are investigated in this paper based on measurements and FEM calculations [1].

2. Measurements and FEM calculations

Fig.1 represents FEM model as an example of assembled structures, which consists of 10 cores, upper/lower panel. This A-type has spot weld elements between cores and lower panel. On the other hand, B-type is continuous structures as upper/lower panel and cores. Fig.2 shows a hydraulic system universal testing machine to evaluate the bending stiffness by 3 points bending mechanism. Comparison between measured data and FEM results for relationship with load and deformation shows FEM results are in good agreement to measured data. Mises stress distribution of A-type (Fig.3) has stress concentration area at the contact area between panels and cores much larger than that of B-type (Fig.4) and deformations of A-type are overall.

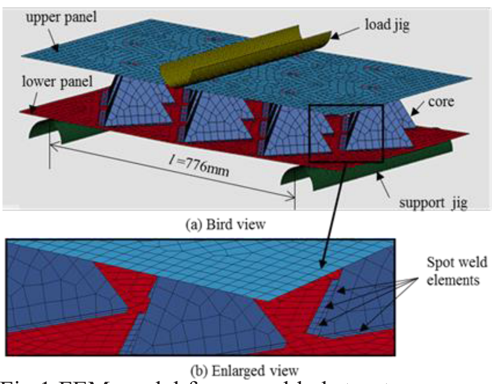
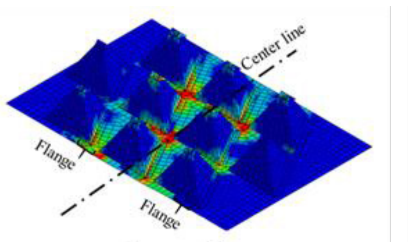
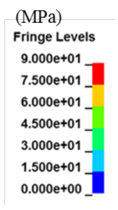


Fig.1 FEM model for assembled structures.
Shell element thickness is 1.5mm.

Fig.2 Assembled structures in the bending test.
Weight of aluminum structures is 6.5kg.





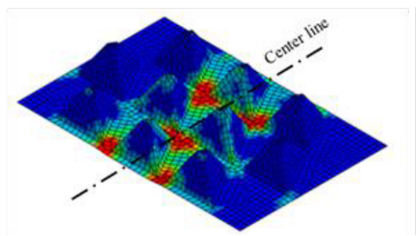


Fig.3 Mises stress distribution of A-type.

Fig.4 Mises stress distribution of B-type.

3. Conclusions

Assembled structures by origami forming that can be produced actually as high flexibility to design, are expected to serve as internal structural reinforcement materials. Characteristics of deformations as them are shown clearly that the stress concentrations generate at many joint points and they deflect overall.

Reference

[1] Terada, K., Tokura, S., Sato, H., Makita, A., and Hagiwara, I., Evaluation of the bending stiffness on assembled lightweight and high strength panel,No.15-00039[DOI:10.1299/transjsme.15-00039],Vol.81,No.828,2015.

The Waterbomb Origami Tube

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1. Introduction

In origami, the waterbomb tube refers to an origami structure made from a paper pattern obtained by tessellation of the so-called waterbomb bases. One of the most distinctive characteristics of the waterbomb tube is that it has a negative Poisson's ratio: when compressed, both its length and diameter get smaller. This has led to a number of notable practical applications including an expandable medical stent graft, a transformable worm robot, as well as a deformable robot wheel. Despite these applications, its precise motion behaviour when being compressed and the resultant mechanical property have remained ambiguous, especially whether the shape change is rigid origami, in which the facets remain flat and un-deformed whilst rotating about bounding creases, or whether the facets themselves have to deform. To know this is critically important for it to be used to create a metamaterial and for other current and future applications. In this talk, I shall uncover the true motion behaviour of the waterbomb tube through a detailed kinematic analysis and structural simulation thereafter.

2. Characteristics of the Watermomb tube

The behaviour of a waterbomb tube depends on its geometric parameters. It turns out that some tubes are capable of transferring between a pure rigid origami to structural deformation under external loadings, and there exists a mechanism-structure-mechanism transition in its motion, Fig. 1. More interestingly, the tube has an inherited ability of being switched among the various rigid motion paths that corresponding to different mechanical properties. The talk will provide detailed information on when this is happening and how it can be tuned. I anticipate that this research will provide a solid foundation for full exploitation of this ancient origami object to create novel metamaterials, shape-changing structures and soft robots.

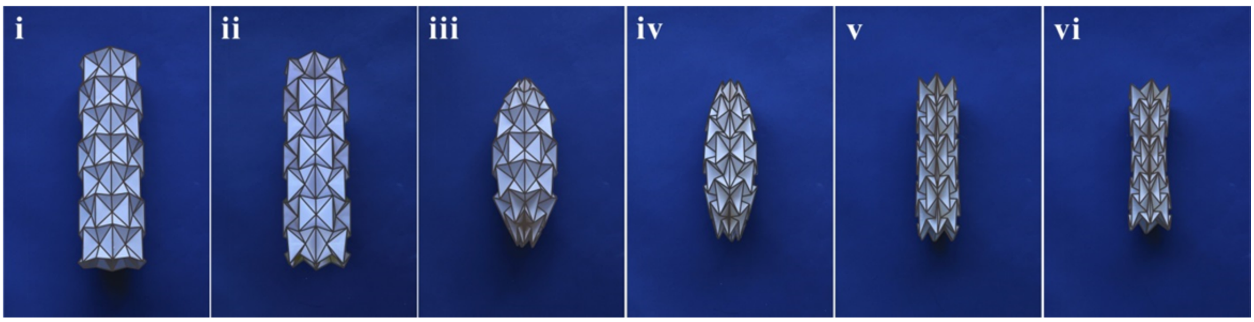

Fig. 1. A waterbomb tube folds from the expanded configuration (i) to the fully contracted configuration (vi). (i) to (iii), and (iv) to (vi) are rigid folding whereas (iii) to (iv) is not.

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International Conference on Mathematical Modeling and Applications 2016
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More information: http://cmma.mims.meiji.ac.jp/eng/

Continuous Flattening of Boxes with Thickness

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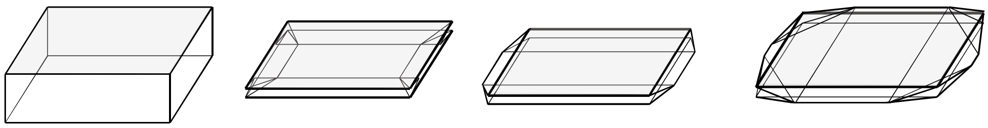
1. Introduction

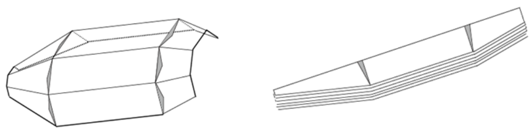
When we want to flatten an empty box, how to manage it? There are many ways to do so; some people may cut and open it, or others may push it by force. Here, we treat such problem a little precisely by using mathematical definitions which depend on materials. First, we consider boxes made of paper with zero-thickness, which means papers can be folded by creases. Next, we discuss on the case that the box is made of rigid faces with suitable hinges (that is, panel-hinges). Finally, we study on the case that the box is made of rigid faces with thickness. For the sake of industrial applications, we prefer methods which are simple and elegant.



(K. Matsubara-C.N.)

2. Continuous motions

The problem of continuous flattening polyhedra made of paper, without cutting and stretching, was originally proposed by E. Demaine, M. Demaine and A. Lebiw in 2001, and .published in 2007 in [2]. If the shape is a convex polyhedron, there were at least three methods given by author et al. In this talk we use the kite method shown in [3, 4] among them, and introduce several ways of flattening a zig-zag belt. We discuss the difference between the ways for crease patterns. The idea may help us to find an efficient way, as we worked on the cupboard foldable helmet shown in the following figures.



If a box is made of thick material, we need to manage the continuous motion for flattening without self-intersection more carefully. There are known results for folding thick panels [1] which we use for flattening boxes with thickness.

3. Future works

There are many polyhedral figures with thickness which are expected to be foldable. Therefore, we would like to continue finding suitable moving crease patterns and places of hinges.

Reference

[1] Yan Chen, Rui Peng, Zhong You. Origami of thick panels. Science, 349 (2015), 396-400.

[2] E. D. Demaine and J. O'Rourke. Geometric folding algorithms, Linkages, Origami, Polyhedra. Cambridge University Press, 2007.

[3] J. Itoh and C. Nara. Continuous flattening of Platonic polyhedral. Computational geometry, Graphs and Applications, 7033, LNCS, Springer -Verlag (2011), 108-121.

[4] C. Nara. Continuous flattening of some pyramids. Elem. Math. 69 (2014), 45-56.

A survey on computational complexity of finding good folded state with few crease width

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1. Introduction

For a given crease pattern, there exists an infinite number of folded states which are consistent of the pattern. More precisely, for a given random string of mountain and valley of length n, there are $f(n)=\Theta(1.65^n)$ folded states on average for a paper strip of length $n+1$ having crease pattern at regular intervals. This function $f(n)$ has upper bound $O(2^n)$ and lower bound $\Omega(1.53^n)$ from mathematical point of view (see [1] for the details). From the practical point of view, among this exponentially many folded states, it is natural to aim to find a good folded state that has better property than the others. From this viewpoint, we introduced a notion of crease width that is the number of paper layers between two paper segments joined at the crease. From the viewpoint of theoretical computer science, we have investigated computational complexity of the minimization problems for crease width. We showed hardness for some problems, and gave some efficient algorithms for the other. A survey of this research will be given.

2. Stamp folding and crease width

We focus on a 1D strip paper of length $n+1$. The input of the problem is a string over “mountain” and “valley” of length n. Then there are exponentially many folded state of unite length of this paper with respect to this string. A special case is that the case of the string “MVMV…” which yields to a pleat folding. The number of folded state is one if and only if the string gives pleat folding. The other case, we have two or more folded state for a given string. It is still open estimation of the number of folded state for a given crease pattern except this pleat case. Especially, we do not know a string of length n that gives most folded state. When a crease pattern is given, it is natural to find a good folded state from the viewpoint of accurate folding and stress of paper. From this viewpoint, we like to minimize the number of paper layers at each crease. We show that this problem is intractable in general in [2]. That is, most cases are NP-complete, which means that we cannot make any program that solves this problem efficiently. We also prove that some cases can be solved efficiently. Precisely, we can find a minimum total crease width when this total value is reasonably small. In the term of theoretical computer science, we show that this problem is fixed parameter tractable in this situation. Recently, we extend the origami model from regular intervals to general case in [3]. That is, we extend the results for regular intervals to general non-regular intervals. We again show that most problems are intractable in this new model.

3. Conclusions

From the mathematical point of view, we have some unsolved problem in stamp folding. Especially, what the most complex string that gives most folded states? From the viewpoint of theoretical computer science, developing efficient algorithms seem to be interesting problem. Extension to 2D is another issue.

Reference

[1] Ryuhei Uehara, Stamp foldings with a given mountain-valley assignment in *ORIGAMI[5]*, pp. 585-597, CRC Press, 2011.

[2] Takuya Umesato, Toshiki Saitoh, Ryuhei Uehara, Hiro Ito, and Yoshio Okamoto, Complexity of the stamp folding problem, *Theoretical Computer Science*, Vol. 497, pp. 13-19, 2012.

[3] Erik D. Demaine, David Eppstein, Adam Hesterberg, Hiro Ito, Anna Lubiw, Ryuhei Uehara and Yushi Uno, Folding a Paper Strip to Minimize Thickness, The 9th Workshop on Algorithms and Computation (WALCOM 2015), Lecture Notes in Computer Science Vol. 8973, pp. 113-124, 2015.

Principle and experimental evaluation of origami-inspired vibration isolators

Sachiko Ishida[1]
Joint work with Kohki Suzuki[1] and Haruo Shimosaka[1]
[1]Department of Mechanical Engineering, Meiji University, Japan

1. Introduction

In this talk, the author shows a principle to isolate vibration using a foldable cylinder with a torsional buckling pattern and experimental results of a prototyped vibration isolator designed based on the principle.

2. Principle to isolate vibration using foldable structures

It has been known that a nonlinear spring with high-static-low-dynamic stiffness is theoretically able to work as a vibration isolator around a static equilibrium position that is in a low-stiffness range [1]. By numerical analysis, it is identified that an origami-based foldable cylinder with a torsional buckling pattern has a high-static-low-dynamic-stiffness-spring characteristics that implies the possibility to apply it to isolator [2].

3. Experimental results

Figure 1 shows a prototyped vibration isolator using versatile mechanical components based on the above-mentioned foldable cylinder. To see the possibility to practical usage, the vibration responses against z-dimensional signals of seismic waves were examined. As a result, it was confirmed that the isolator enabled to mitigate vibration at high frequency range (Figure 2). On the current configuration, the applicable frequency range is over 6 Hz, which is to be improved for the future.

Figure 1 Prototyped vibration isolator. The figure was extracted from [3].

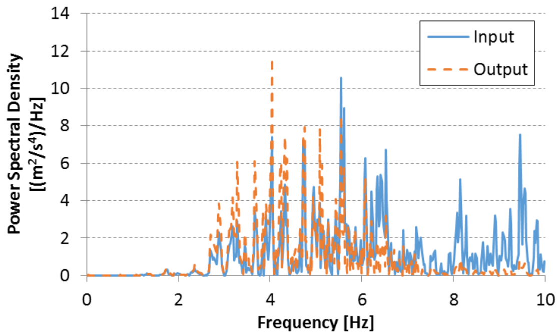

Figure 2 Seismic waves generated on the Tohoku-Pacific Ocean Earthquake and response waves by the prototyped isolator. The figure was extracted from [3].

Reference

[1] Carrella, A., Passive Vibration Isolators with High-Static-Low-Dynamic-Stiffness, VDM Publishing, 2010.

[2] Ishida, S., Uchida, H., Shimosaka, H., and Hagiwara, I., Design Concepts and Prototypes of Vibration Isolators Using Bi-stable Foldable Structures, Proceedings of ASME 2015 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, DETC2015-46409.

[3] Ishida, S., Suzuki, K., and Shimosaka, H., Design and Experimental Analysis of Origami-inspired Vibration Isolators with Quasi-zero-stiffness Characteristic, Proceedings of ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC2016-59699.

ICMMA 2016

Folding Paper: Visual Art Meets Mathematics

Erik Demaine
Massachusetts Institute of Technology, USA

My father Martin Demaine and I like to blur the lines between art and mathematics, by freely moving from designing sculpture to proving theorems and back again. Paper folding is a great setting for this approach, as it mixes a rich geometric structure with a beautiful art form. Mathematically, we are continually developing algorithms to fold paper into any shape you desire.

Sculpturally, we have been exploring curved creases, which remain poorly understood mathematically, but have potential applications in robotics, deployable structures, manufacturing, and self-assembly. By integrating science and art, we constantly find new inspirations, problems, and ideas: proving that sculptures do or don't exist, or illustrating mathematical beauty through physical beauty. Collaboration, particularly as a father-son team, has been a powerful way for us to bridge these fields. Lately we are exploring how folding changes with other materials, such as hot glass, opening a new approach to glass blowing, and finding new ways for paper and glass to interact.

Four-dimensional origami model of the alveolar structure in the human lung

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1. Introduction

The alveolar system in the mammalian lung is one of the most complicated structures in the living organ. The air pathway is space-filling in spite of a part of a rooted tree originated from the trachea, and its configuration changes during respiratory cycle. I previously proposed a computational model of the 4D alveolar structure [1], but very few people understood it because of geometric complexity. Then, I have constructed an origami model which is almost equivalent to the computational model[2]. One can make a real solid model by oneself, and understand how it would be moved during respiratory cycle.

2. Single origami alveolus

The left part in Fig.1 indicates a sheet for a single alveolar origami model. When neighboring edges of ping parts are connected by cellophane tape, the sheet becomes a 3D object, and a pink ring, corresponding to the alveolar mouth, is generated. As the pink ring is folded at black lines, its opening becomes smaller, and finally is closed (right part in Fig.1). The whole volume becomes the minimum when the ring is closed. This behavior mimics the real alveolar defamation during respiratory cycle.

3. Origami alveolar duct

The alveolar duct is an air duct whose wall is completely replaced by several alveoli. Therefore, the origami duct is generated by connecting single origami alveoli in 3D space (left in Fig 2). Branching and space-filling duct system is generated by connecting multiple duct units (right in Fig 2).

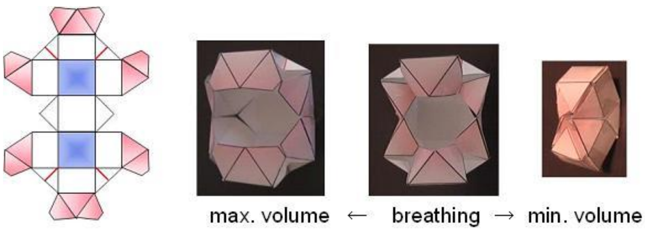

Fig.1 Single alveolar model.

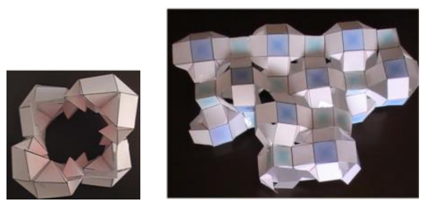

Fig.2 Alveolar duct model

3. Conclusions

My 4D alveolar model in computer had been neglected for several years, because it was inconsistent with conventional respiratory physiology and pathophysiology. Owing to the origami modelling, novel understandings for alveolar structure and function are spreading in medical people. Seeing is believing. I dare say "Making is convincing".

Reference

[1] Kitaoka H, Nieman GF, Fujino Y, Carney D, DiRocco J, Kawase I. A 4-dimensional model of the alveolar structure. *J Physiol. Sci.* 57: 175-185, 2007.

[2] Kitaoka, H. A 4D model generator of the human lung. *Forma* 26: 19-24, 2011.

Formation of 3D co-culture microstructures using MEMS and Origami folding techniques

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1. Introduction

Interactions between different kinds of cells play an extremely important role for cell functions and proliferation [1, 2]. Recently, many methods to produce 3D co-culture structures have been developed [3, 4], however, they are complicated, and the shapes of the 3D structures are restricted. We have developed a method to produce 3D cell-laden microstructure which formatted by cell traction force as the motive power [5]. This technique solved the above problems. It is easy and rapid to format and the shape can be changed simply. Our previous results observed by confocal microscope showed a hollow inside of dodecahedron 3D microstructure after folding. Therefore, it is possible to culture other kinds of cells in the hollow and create 3D co-culture microstructures.

2. Method of forming 3D co-culture microstructures

Cells were cultured the micro-sized plates that was fabricated on a glass substrate by a standard lithography technique of micro electro mechanical systems (MEMS). In order to make sure that the cells will only stay on the microplates, 2-methacryloyloxyethyl phosphorylcholine was (MPC) coted on the substrate (Fig. 1). In this research, we use 3T3 and HepG2 cells to form the 3D co-culture microstructures. This method for cells culture is the same as conversional 2D culture without any other complicate processes. After these processes, alginate lyase was applied to remove alginate that was a sacrificial layer (Fig. 1), and the microplates were folded to format the 3D co-culture microstructures because of the traction forces of 3T3 cells. Finally, the location of 3T3 and HepG2 cells was determined.

3. Results

We successfully formed the 3D microstructure and co-culture of 3T3 and HepG2 cells. HepG2 cells located in the central of microstructure were surrounded by 3T3 cells which distributed in the periphery (Fig 2). The folding time can be controlled by using alginate comparing with using gelatin in previous research [5], and a number of 3D microstructures can be folded at one time during 1 to 2 minutes.

The 3D co-culture HepG2 and 3T3 cells system can be easily acquired by applying microplates formatted 3D cell-laden microstructures. And the specific hepatic genes and the drug metabolism will be detected for investigation of function and response of co-culture microstructure.

Acknowledgments

The authors are grateful to Takahiro Okajima for his useful discussions and Kazuhiko Ishihara for porviding MPC polymers. This work was supported by JSPS KAKENHI Grant-in Aid for Scientific Research (B), Grant Number 26286030.

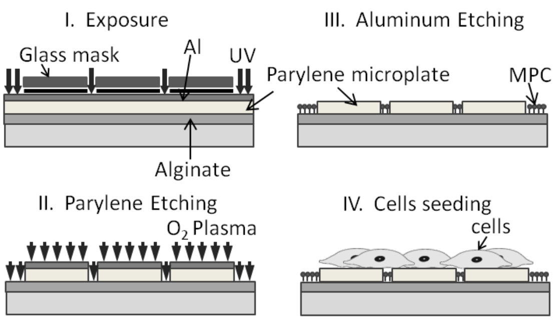

Figure 1 The processes of microplates formation

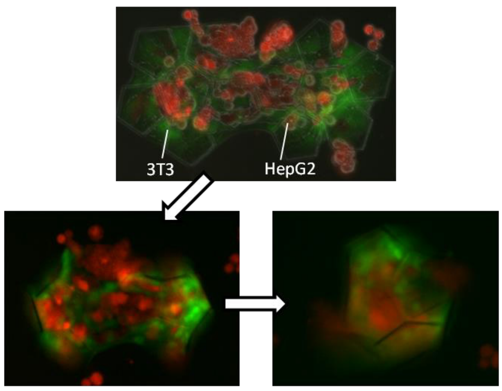

Figure 2 The 3D co-culture system of 3T3 and HepG2 cells

Reference

[1] Shimaoka S, Nakamura T and Ichihara A, Exp Cell Res, 172(1) (1987), 228-242.
[2] Tsuda Y, Kikuchi A, Yamato M and et al, Biochem Biophys Res Commun, 348(3) (2006), 937-944.
[3] Matsunaga YT, Morimoto Y and Takeuchi S, Adv Mater, 23(12) (2011), H90-94
[4] Yamada M, Utoh R and Ohashi K, Biomaterials, 33(33) (2012), 8304-8315
[5] Kuribayashi-Shigetomi K, Onoe H and Takeuchi S, PLoS One. 7(12) (2012), e51085

Development of a Paper-based Rapid Prototyping System for Orthopaedic Surgical Planning

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[1]Meiji Institute for Advanced Study of Mathematical Sciences, Japan

1. Introduction

3D printing or rapid prototyping (RP) has emerged as a revolutionary technique that overcomes the limitations produced by the use of flat screens and 2D drawings for the visualization of three-dimensional (3D) imaging data by producing graspable 3D objects which can be applied for surgical planning, training, prosthetics and related applications. 3D printing may be costly but in complicated surgical cases, additional costs of RP may be compensated by reduced operating times and higher success rate of the surgical procedure. The time needed for producing a 3D object limits its use in surgery to elective cases and makes it unsuitable for emergency cases. In order to overcome above limitations we have been working on the development of a new RP system that incorporates a new origami-pattern generation algorithm to produce paper-based copies of physical objects [1]. Figure 1 shows the general flowchart of our current research that deals with two problems: 1) the generation of 3D digital models from X-ray images [2] and 2) the development of a paper-folding robot by direct teaching from experiments [3] in order to speedup the creation of paper-models by proposed folding machines [4].

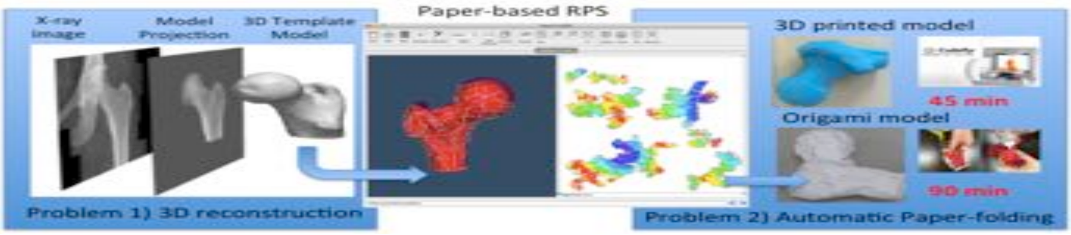

Figure 1: General flowchart of the proposed research

2. Bone Shape Modeling and Paper-based Construction by "Norigami" Folding Machines.

Figure 2 (left) shows a comparison of a model of a Tibia constructed from X-ray images using [2], printed with Cube 3D printer and proposed method [1]. Three folding trajectories in Fig.2 (middle) are used to create a round object by proposed "norigami" folding machines (right). Feed-forward control is needed to reduce the error of the machines. Two neural networks (i.e. ADALINE and proposed HNN) are compared to follow the trajectories. HNN is faster and average error in the folding position by HNN is 2 times smaller than ADALINE's error (~2.6mm vs ~5.6mm).

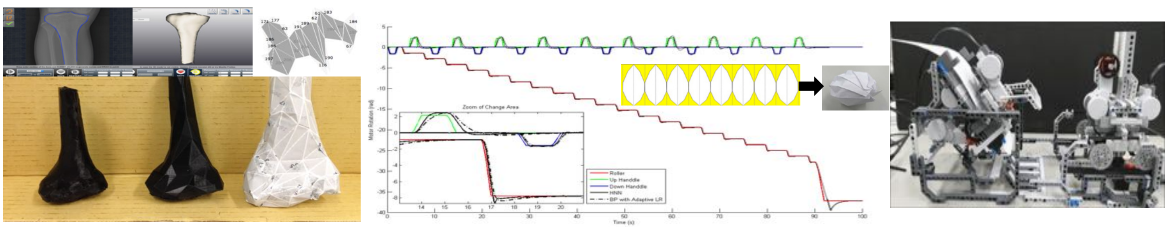

Figure 2: Models of a right tibia and "Norigami" folding machines with folding trajectories for a round object

References

[1] B. Yu, M. Savchenko, J. Shinoda, L. Diago, I. Hagiwara and V. Savchenko "Producing Physical Copies of the Digital Models via Generating 2D Patterns for "Origami 3D Printer" system", Journal of Advanced Simulation in Science and Engineering, Vol. 3 (2016) No. 1 p. 58-77.

[2] V. Karade and B. Ravi, "3D femur model reconstruction from biplane X-ray images: a novel method based on Laplacian surface deformation" Int J CARS Vol.10 (2015) No. 4 p. 473-485.

[3] Y. Kihara and Y. Yokokohji, "Skill Transfer from Human to Robot by Direct Teaching and Task Sharing: A Case of Study with Origami Folding Task" In 11th IFAC Symposium on Analysis, Design, and Evaluation of Human-Machine Systems Vol. 11 (2010) p. 454-459

[4] J. Romero, L. Diago, J.Shinoda, C. Nara and I. Hagiwara. "Norigami Folding Machines for Complex 3D Shapes" In Proc. ASME IDETC/CIE (2016) (in Press)

Cube Division - Old and New Artistic Exercise -

Maekawa Jun[1]
[1]Origami Artist

1. Introduction

Dividing a cube in various ways to see diverse sections is an effective exercise for artistic design. It has been practiced by some educational programs including Bauhaus in German and Kuwasawa Design School in Japan, and has resulted in some art works including "Wine Cube" by Hiroshi Tomura[1]. It is also a useful educational material for Mathematics. The following geometric fact is well-know:

When a cube is divided with a plane, the section can be a square, an equilateral triangle, a rhombus, a rectangle, a regular hexagon, and so on, but cannot be a regular pentagon.

2. Origami works

Some origami works have also designed on cube division, including:

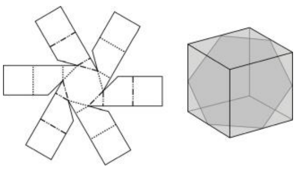

Figure 2-1.
Cube with a regular hexagon [2].

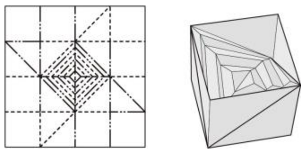

Figure 2-2.
Cube with a hyperbolic paraboloid[3].

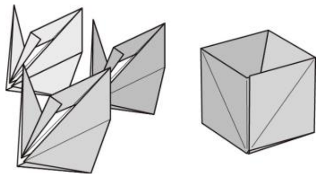

Figure 2-3.
Cube trisection (modular origami)[4].

3. An application

While studying cube division origami models, the author came up with an idea that does not have direct connection with origami techniques.

Basic measuring spoons for cooking have volumes 15cc, 10cc, and 5cc, which are 1/2, 1/3, and 1/6 of 30cc, respectively. Meanwhile, a cube can be divided in 1/3 or 1/6 easily because, as we have seen in 2-3, it has rotational symmetry of order 3. Noticed these facts, the author devised a spoon that can measure three different volumes by rotating three axes.

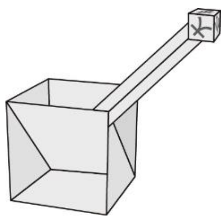

Figure 3-1. Large, medium, and small integrated measuring spoon

References

[1]Tomura H.　“Kihon Keitai no Kozo”, Bijutsu Shuppan Sha, 1974

[2]Hull T., “Origami^3 Third International Meeting of Origami Science, Mathematics, and Education”, A K Peters, 2002

[3]Maekawa J. , “Oru Kikagaku(Folding Geometry)”, Nippoon Hyoron Sha, 2016

[4]Maekawa J. , “Otte Tanoshimu Origami Seminar”, Sugaku Seminar, Vo;. 55 No. 5(2016), pp. 88-89

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Tilt-up concrete dome skeleton construction by Rotational Erection System (RES)

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[1]Aichi Institute of Technology, Japan

1. Introduction

We propose a novel construction method for dome skeleton using Tilt-up concrete and Rotational Erection System (RES)[1]. The construction procedures are 1) setting the edge form and rebar on the level floor pad, 2) casting structural concrete, 3) hoisting up the hub on the temporary support, 4) tilting-up the arms and fastening them to the hub. We studied the two types of rigid frame configuration with a) intersecting arms and b) dual layer arms and one type of cable-stay configuration (Fig. 2) [2,3]. We investigated a modification to RES for rigid folding that would be applicable to the alternative jack-up erection method with fully linked elements.

2. Three types

We apply RES geometry to determine the efficient layout of the concrete forms on the floor slab (Fig. 1). The interactive parametric design tool written in GeoGebra was used to find the arm profile appropriate for the concrete structure.

3. Structural analysis

FEM Structural analysis showed 30m span domes in the three configurations are feasible with the conventional concrete materials. The seismic load C_0=0.5 was applied as the critical condition (Fig. 3).

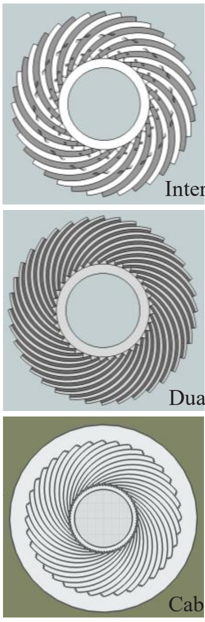

Fig. 1 Patterns.

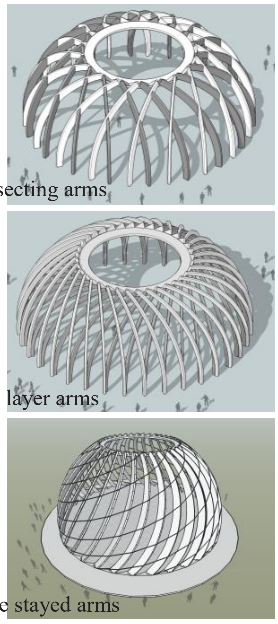

Fig. 2 Dome types.

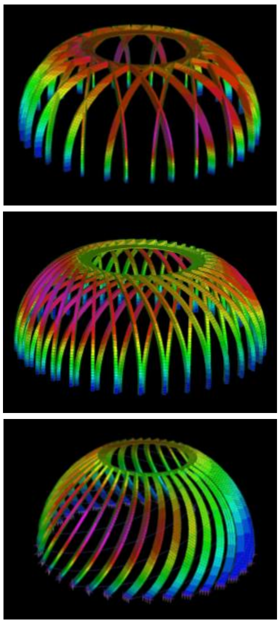

Fig. 3 Displacements.

4. Rigid foldable RES

Adding two hinges for each arm at the hub make RES rigid foldable (Fig. 4).

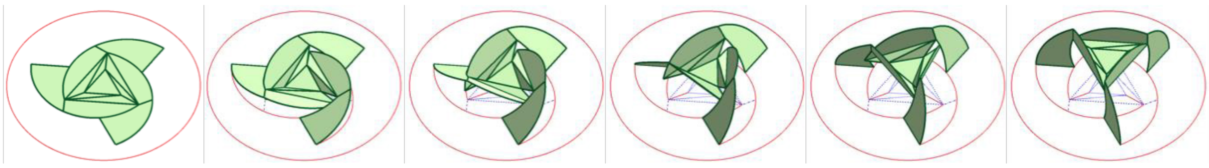

Fig. 4 Rigid folding sequence (RES n=3, α= 60°, β= 90°).

5. Conclusions

Taking advantage of existing know-how of tilt-up concrete method, RES could achieve the visual effect and special impression that was never done with tilt-up concrete. Further parametric optimization and refinement in the construction procedure would find a competitive position among the existing construction methods.

Reference

[1] Miyamoto Y., Rotational Erection System (RES): Origami Extended with Cuts, in Origami6 II: Technology Art, Education, Miura K (ed.), AMS, 2015, 537-544.

[2] [3] Miyamoto Y., Itoh T., Harada H., Tilt-up concrete dome skeleton construction by Rotational Erection System (RES), part 1 & 2, Proceedings of the IASS Annual Symposium 2016.

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An iterative simulation-based design of the origami-performing robot

Maria Savchenko
Meiji Institute for Advanced Study of Mathematical Sciences

Abstract

The robot design based on experiment only is difficult, expensive, and time-consuming. Then the simulation approach based on software becomes the main option in the real-world related with a robotic activity for creating basis for hardware design. We present a study: the iterative simulation-based design of the origami-performing robot's hardware. The basic premise underlying the study is that each folding operation of the crease patterns of origami is considered as a function of the mechanical systems such as a robot. The aim of the research is to manipulate the foldable objects such as a sheet of paper in the simulation environment in the relation with understanding the robot design instead of creating the real robotic prototypes. In this case, dynamic and kinematic behaviour of the robot arms in the formation of origami models can be simulated by using LS-DYNA software. In simulating, we consider two types of crease patterns: i) in ordinary paper folding; ii) in the thickened paper folding. In the both cases the goal of the simulation is to form the 3D origami models. Fig.1 illustrates the design process from the schematic stage to the final design. Fig.2 shows forming a bending crease and the 3D shapes by the robot end-effectors in the finite element models of crease patterns.

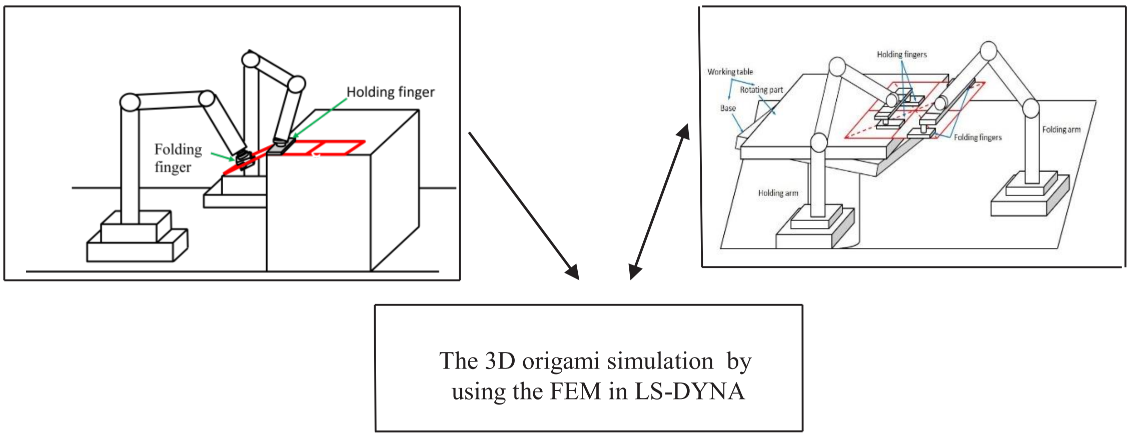

Fig.1 Design process: schematic stage- simulating - the final design stage

Fig.2 Results of the simulation: ordinary paper and carton models

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Some observation of regular polygons in origami paper

Haruo Hosoya

Department of Information Sciences, Ochanomizu University (Emeritus), Japan

1. Introduction

The standard size of origami paper in Japan is 15cm×15cm, from which I have found several interesting ways for cutting out regular polygons. Although metric ruler and scissors are necessary for these operations, I believe that these findings are helpful not only for mathematics education to junior high school students but also for popularization of origami to the public. In this talk the secret of "Nana-kin-san Silhouette Puzzle (Golden Heptet Triangles)" will also be disclosed, which is motivated from the pair of golden triangles and was recently designed by me.   .

2. Patterns

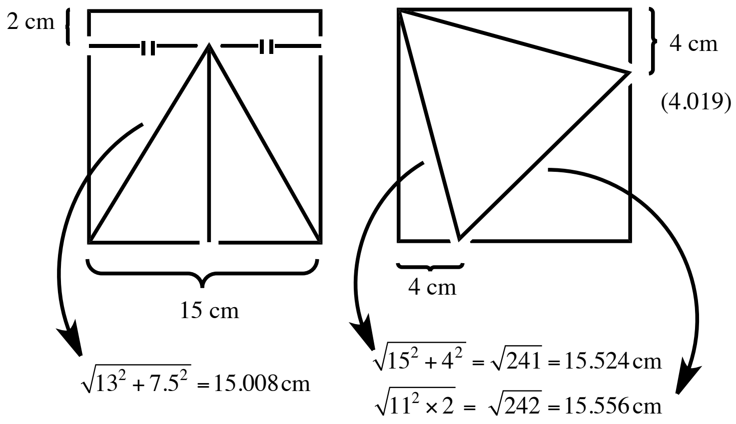

Fig. 1. Largest triangles in origami.

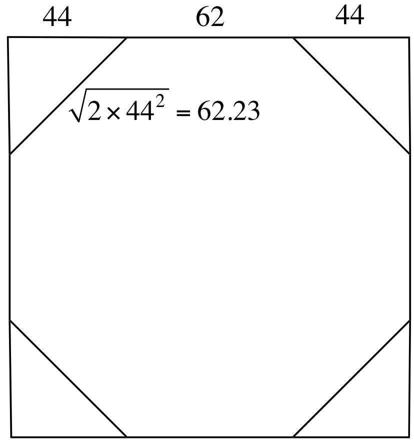

Fig. 2. Largest octagons in origami.

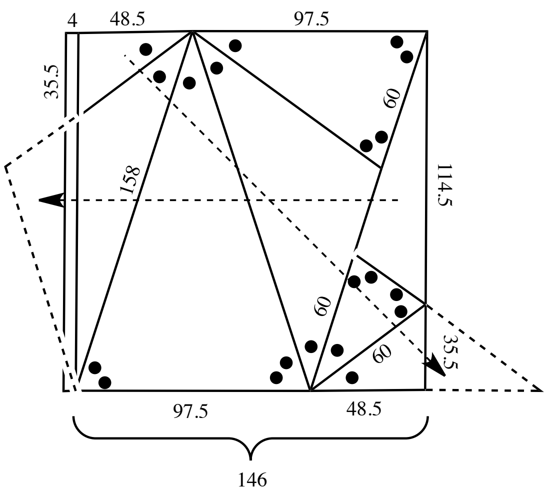

Fig. 3. Relation among golden triangles, regular pentagon and square.

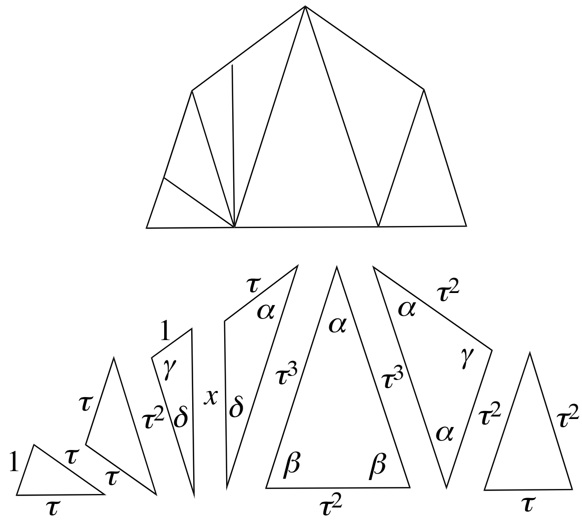

Fig. 4. Golden Heptet Triangles.

References

[1] H. Hosoya, Seven Secrets of Triangles (in Japanese), Blue Backs, B-1823, Kodansha, Tokyo, 2013.

[2] Golden Heptet Triangles, Manufactured by Image Missions Inc., Shizuoka, 2015.

Paper Models of Projection of 4-dimensional Regular Polytopes

Koji Miyazaki
Professor Emeritus, Kyoto University, Doctor of Engineering

Abstract

In this paper, the real shape of each face of orthogonal projection into 3-space of 4-dimensional regular polytopes are shown to make their Origami-like handmade models. The result will serve to flourish the world of paper models which is active in 4-space.

Unique point of this paper

There are 6-kinds of regular 4-polytopes: the 5-, 8-, 16-, 24-, 120-, and 600-cell (Fig.1, from top to bottom rows). They are composed of 3-dimensional regular polyhedra and can be orthogonally projected into 3-space in typical 4 types: vertex-, edge-, face- and cell-centered projections (Fig.1, from left to right column).

In spite of such variety, merely some of simple vertex- or cell-centered projections are usually adopted as projections of regular 4-polytopes because of usefulness for easy understanding and manufacturing.

To make innovations such present conditions, in this paper, the real shape of each face which composes all projections shown in Fig.1 are represented.

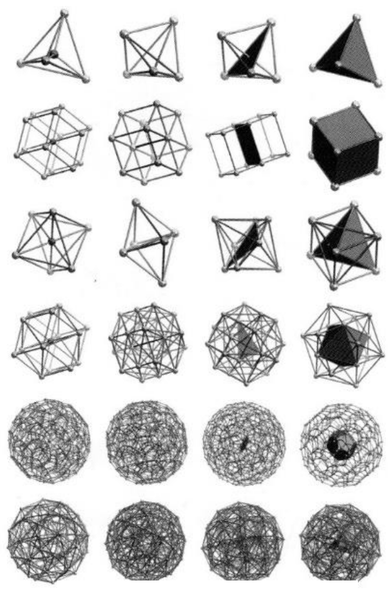

Fig.1

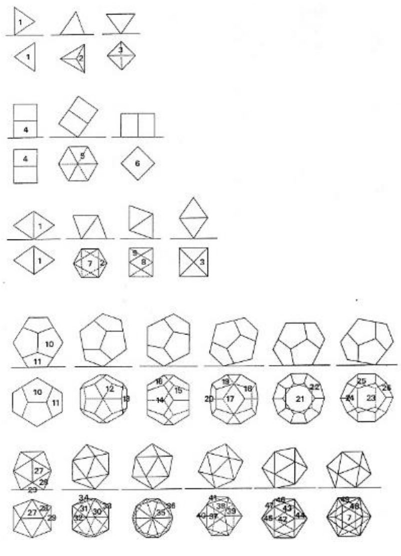

Fig.2

Conclusion

The real shape of each face of projections shown in Fig.1 coincides with any of the numbered plans or elevations of rotational 3-dimensional regular polyhedra as is shown in Fig.2. Each polyhedra composes any of regular 4-polytopes.

Fig.3 shows Origami-models representing orthogonal projections of regular 4-polytopes constructed by the real shapes shown in Fig.2. Each is composed of small flattened regular polyhedra shown below.

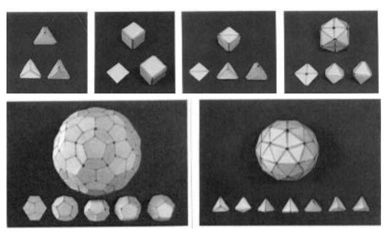

Fig.3

Computing Area, Circumradius, and their Integrated Formulae for Cyclic Polygons

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1. Introduction

In this study, we consider a classic problem in Euclidean geometry for cyclic polygons; that is, n-gons inscribed in a circle, given by the length of sides $a_1, \ldots, a_n$. In particular, we focus on the relation between the area S and the circumradius R of cyclic pentagons and hexagons.

The classic results derived by Heron in the 1st century gives the formulae for triangles. For cyclic quadrilaterals, Brahmagupta's formula was obtained in the 7th century. Nowadays, we can rewrite the formulae for $n = 3,4$ into unified and simplified forms as follows, using elementary symmetric functions $s_1 = a_1^2 + a_2^2 + a_3^2 + a_4^2, \ldots, s_4 = a_1^2 a_2^2 a_3^2 a_4^2$:

Area ($x = (4S)^2$): $x - (-s_1^2 + 4s_2 + \varepsilon \cdot 8\sqrt{s_4}) = 0$

Circumradius ($y = R^2$): $(-s_1^2 + 4s_2 + \varepsilon \cdot 8\sqrt{s_4})y - (s_3 + \varepsilon \cdot s_1\sqrt{s_4}) = 0$

Integrated ($Z = (4SR)^2$): $Z - (s_3 + \varepsilon \cdot s_1\sqrt{s_4}) = 0$

In these expressions, ε is called *crossing parity* with 0 for a triangle, 1 for a convex quadrilateral, and -1 for a non-convex quadrilateral. Our goal is the computation of these types' formulae for polygons $n \geq 5$, which remained unsolvable for 1,300 years since Brahmagupta.

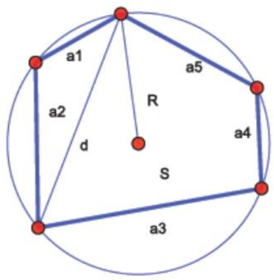

Fig.1 A cyclic pentagon

n	Area formula	Circumradius formula	Integrated formula
5	Robbins (1994) Pech (2006) Moritsugu (2015)	Takebe (1683) Izeki (1690) Robbins (1994) Pech (2006)	Moritsugu (2014) Moritsugu (2015)
6	Robbins (1994) Moritsugu (2015)	Moritsugu (2011, 2016)	Moritsugu (2015)
7	Maley et al. (2005)	Moritsugu (2011, 2016)	(unsolved)
8	Maley et al. (2005)	(unsolved)	(unsolved)

Table 1 Contributions to each formula

2. Algorithms and results

We applied elimination algorithms by resultant using computer algebra systems. Table 1 shows the recent results. We should note that old Japanese mathematicians in the 17th century had already solved circumradius problem for pentagons based on the theory of resultants. Meanwhile, the area formula discovered by Robbins in 1994 was a great breakthrough. In contrast, the author's main contributions are the following computation:

(1) The area formulae ($n = 5,6$) by only simple elimination method

(2) The circumradius formulae ($n = 6,7$) and their compact expressions by elementary symmetric functions

(3) The integrated formulae ($n = 5,6$) which have been "missing" since Brahmagupta

To our best knowledge, we believe that these results are quite original.

References

[1] Moritsugu, S., Computing Explicit Formulae for the Radius of Cyclic Hexagons and Heptagons, Bulletin of JSSAC, Vol.18, No.1, pp.3-9, 2011.

[2] Moritsugu, S., Integrated Circumradius and Area Formulae for Cyclic Pentagons and Heptagons, ADG 2014, Lecture Notes in Artificial Intelligence, Vol.9201, pp.94-107, 2015.

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On the Enumeration and Counting of Developments of Polyhedra

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1. Introduction

A development of a polyhedron is a simple polygon obtained by cutting along edges of the polyhedron and unfolding it into a plane. The cut edges of a development of a polyhedron form a spanning tree of the 1-skeleton (i.e., the graph formed by the vertices and the edges) of the polyhedron, and vice versa. In this talk, we discuss the techniques for enumerating developments of polyhedra and counting the number of developments.

2. Enumeration of developments

We use ZDDs (zero-suppressed binary decision diagrams) for enumerating developments of polyhedra (i.e., spanning trees of the 1-skeletons) [1, 2]. A ZDD is a directed acyclic graph representing a family of sets. Fig. 1 is an example of a ZDD representing {{e1, e3, e5}, {e1, e4}, {e2, e3, e4}, {e2, e5}}. Each path from the root node to the 1-node (the sink node labeled “1”) corresponds to a set. The paths e1-e3-e5-1 and e1-e3-e4-1 in Fig. 1 respectively correspond to {e1, e3, e5} and {e1, e4}. Note that the labels of the nodes with dotted edges are ignored. Figs. 2 and 3 illustrate partial lists of the developments of a dodecahedron and an icosahedron, respectively.

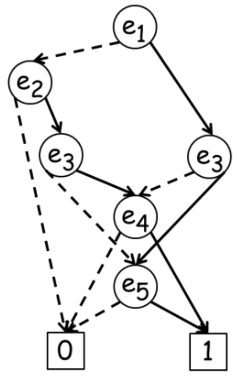

Fig. 1 ZDD.

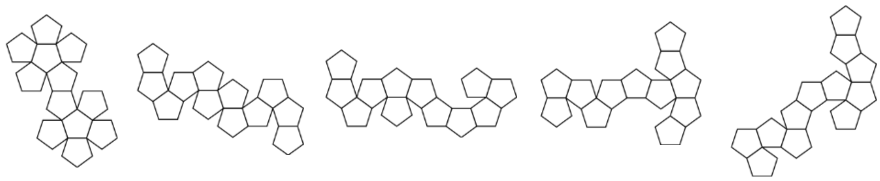

Fig. 2 Partial list of the developments of a dodecahedron.

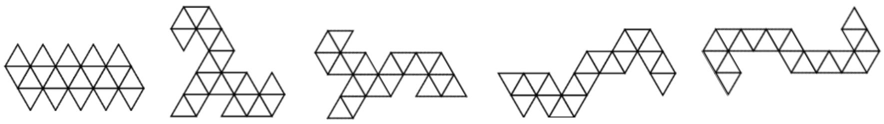

Fig. 3 Partial list of the developments of an icosahedron.

3. Counting the number of developments

The easiest way for counting the number of developments of a polyhedron is to enumerate those and count the number of obtained ones. By utilizing the group theory, however, we can count the number of developments without enumerating them[3]. In this talk, we will give the number of developments of Archimedian solids.

Reference

[1] T. Horiyama, and W. Shoji. Edge-Developments of Platonic Solids Never Overlap, In Proc. of the 23rd Canadian Conference on Computational Geometry (CCCG 2011), pp. 65-70, 2011.

[2] J. Kawahara, T. Inoue, H. Iwashita, and S. Minato. Frontier-based Search for Enumerating All Constrained Subgraphs with Compressed Representation, Technical Report TCS-TR-A-14-76, Division of Computer Science, Hokkaido University, 2014.

[3] T. Horiyama, and W. Shoji. The Number of Different Unfoldings of Polyhedra, In Proc. of the 24th International Symposium on Algorithms and Computation (ISAAC 2013), Lecture Notes in Computer Science, vol. 8283, pp. 623-633, 2013.

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More information: http://cmma.mims.meiji.ac.jp/eng/

Modeling by the infinite fold

Tomoko Fuse

Origami Artist, Independent

1. Introduction

Folding a sheet of paper sometimes results in unintentional discovery of an interesting shape, sometimes in finding a rhythm of folds. Modeling by folding paper is more constrained than other genres of art. That is the reason why the found shapes are usually geometrical.

As examples of such findings, the author reports some works with the infinite fold, where folding patterns can be repeated endlessly: two-dimensional tessellation pieces and three-dimensional accordion-like works.

2. Two-dimensional works

Most of origami pieces involve sequences of bisection. The most common technique is dividing into smaller parts (figure 1). In tessellation, the basic fold is the square twist (figure 2).

Figure 1.[1]

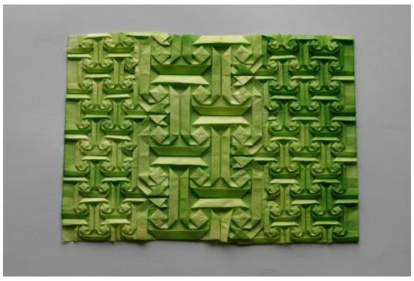

Figure 2.

3. Three-dimensional works

Bisection is also the major technique in three-dimensional models. The author presents five types of pieces with their variations that can be closed flat (figure 3) (figure 4).

Figure 3.

Figure 4.

4. Conclusion

The infinite fold has various types, both two- and three-dimensional. Its pieces have shapes that emerge from the rules of origami, not that represent known shapes or nature. The most important thing is that a complete world can be perceived in the actual folding process.

Reference [1] Shuzo Fujimoto, *Ajisai-ori,* Seibundo Shinkosha, December 2010.

Folding of Deployable Membrane Space Structures

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1. Introduction

The folding/deployment techniques in space engineering are significant to realize satellites, space antennas, and space stations, because the limited volume and weight of capacity for launching the equipment by rocket as well as the increasing size of it due to the complex space missions. As the results, to fold structures on the ground and to deploy easily in space environment are requested. Recently, several deployable membrane space structures have been proposed and constructed, for de-orbiting satellites within 25 years after the completion of their primary missions. Furthermore, membrane structures will enable innovative missions including solar sails, solar arrays, phased array antennas, and sun shields. This paper introduces boom-membrane integrated space structures for small satellites.

2. Boom-membrane integrated space structures

For small satellite, the retraction size and the easy deployment with small deployment mechanisms are important to design the deployable membrane. We have proposed the rotationally skew fold (Fig.1). This folding pattern enables the membrane to be stowed in a desired height of fold pitch without increasing the number of tangential fold lines. The deployment of the membrane is performed by the self-deployable boom in Fig.2. Finally the boom-membrane integrated structures are configured as shown in Fig.3. The deployment procedures are indicated in Fig.4.

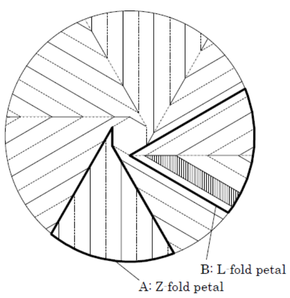

Fig.1 Rotationally skew fold.[1]

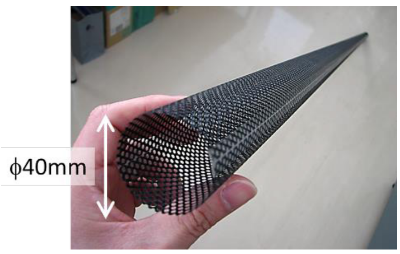

Fig.2 Triaxially woven CFRP

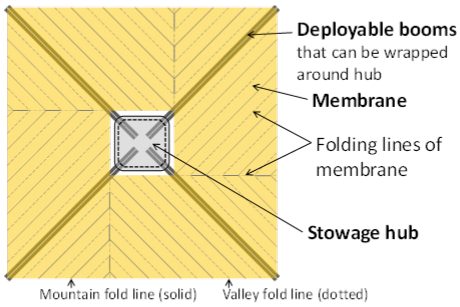

Fig.3 Deployed configuration

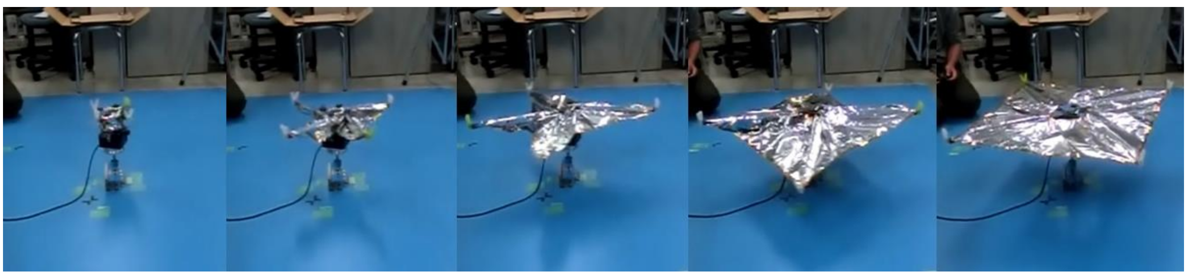

Fig.3 Deployment procedures with cable suspension system.

Reference

[1]Furuya, H. and Masuoka, T., Concept of Rotationally Skew Fold Membrane For Spinning Solar Sail, CD-ROM Proc. 55th International Astronautical Congress, IAC-04-I.1.05, Vancouver, (2004), pp.1-5.

[2]Furuya, H, Mori, O., Sawada, H., Okuizum, N., Shirasawa, Y. Natori, M., Miyazaki, Y., Matunaga,S., "Manufacturing and Folding of Solar Sail "IKAROS"," 12th AIAAGossamer Systems Forum, Denver, AIAA-2011-1967, (2011), pp.1-4.

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Enumeration of formal crease patterns in the square/diagonal grid and verification of their flat-foldability

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1. Introduction

The square/diagonal grid (Fig. 1(a)), which consists of arrayed squares and their diagonals, is commonly used not only in basic origami design but also in the basic structure of recent *self-folding origami robots*[1]. However, the number of shapes made by folding lines of the subset of the grid pattern is not known as far as we have surveyed.

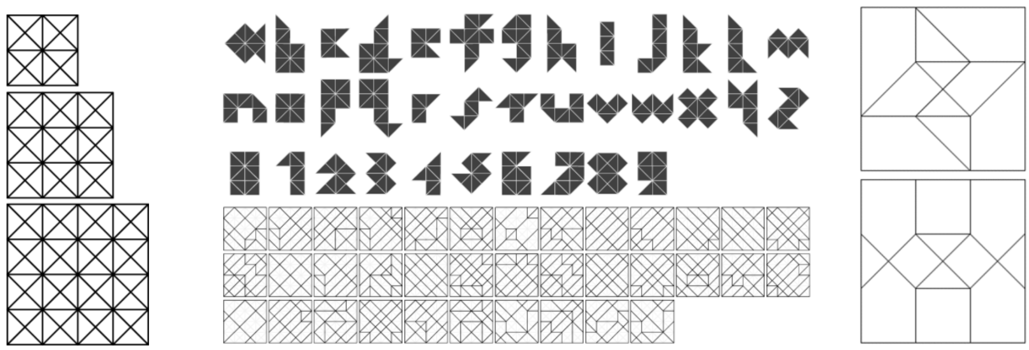
2. Locally flat-foldable crease patterns and their folded shapes

We enumerated the number of *locally flat-foldable crease patterns*[2] and their folded shapes without considering mountain/valley parity. The numbers of crease patterns and the folded shapes in 2x2, 3x3, and 4x4 gird patterns we enumerated are: {116/27}, {58,530/ 366}, and {259,650,300/13,452} respectively.

We verified that all the shapes are realizable, i.e. actually flat-foldable with a physical sheet without self-intersections. At the same time, we found some locally flat-foldable crease patterns that are impossible to be folded.

3. Conclusions

We developed an application to search for a crease pattern that is folded into a shape specified by the user. By using this application, we found the shapes of the alphabet and numbers as shown in Fig. 1(b). In addition, we concluded that the two crease patterns shown in Fig. 1(c) are the smallest and simplest non-flat-foldable ones.



(a) (b) (c)

Fig.1 (a) 2×2, 3×3, and 4×4 square/diagonal grid patterns. (b) Examples of folded shapes and their crease patterns in the 4x4 grid pattern. (c) The simplest and smallest impossible-to-flat-fold crease patterns.

Reference

[1] E. Hawkes, B. An, N. M. Benbernou, H. Tanaka, S. Kim, E. D. Demaine, D. Rus, R. J. Wood, “Programmable matter by fold-ing”, Proceedings of the National Acade-my of Sciences, 2010.

[2] Thomas C. Hull, “The Combinatorics of Flat Folds: A Survey”, Origami3: The Third International Meeting of Origami Science, Mathematics, and Education, 2002.

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Folding Patterns and Deployment Processes in Morphological Changes of Insects

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Insects need several ecdysis processes, since they have external skeleton.

Especially through eclosion processes, they deploy thin membrane structures from highly packed situation.

Influx of body fluid into branching veins induces deployment of membrane wings.

We show eclosion processes of some insects and folding patterns of membranes inside their sheaths.

Origami Based Responsive System Proposal for a Building Surface

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METU Department of Architecture

Introduction

Architecture is not just a response to the needs but is always a manifestation of the available technology of its age. Today both these needs and enabling technologies are increasing symmetrically and become more and more complex. In addition to these advents, increasing number of environmental problems and their severity force architecture to investigate new and innovative design approaches, new challenging forms and materials as well as new construction /fabrication /manufacturing technologies.

Responsiveness in architecture either to soft (social, economic, cultural etc.) or to hard (light, energy, earthquake natural disasters etc.) conditions is always a design goal. In present, computational design approaches related parametric/generative models together with developments in electronics, mechatronics, control systems allow architects to re-explore responsiveness with the use of many interesting kinetic structures.

The Design of the Component

Responsive system design in architecture is a culmination of computational design knowledge and knowledge on dynamics and related enabling technologies. Thus teaching and learning responsive architecture in the present context necessitates modifying curriculum as well.

In this study, design and development of a kinetic surface based on origami is presented. Origami is always a source of inspiration for architects. It is possible to see many building forms derived from origami folding.

However it is still novel to integrate real kinetic building structures based on origami due to material, design and/or kinetic constraints and their implementations. In the present study a kinetic component but also the space itself, which can be transformed and provide different ambient conditions is shown.

In the design process, it is required developing a system to adopt different natural light conditions, various natural ventilation levels and possibility of having different volumetric relations.

The parametric/generative computational model is developed by using Grasshopper and the fabricated prototype is run by Ardunio responding to light and air movement. The basic design idea is shown in Figure 1. The initial form is obtained by truncating the a simple nurb surface, than each surface is folded in two directions.

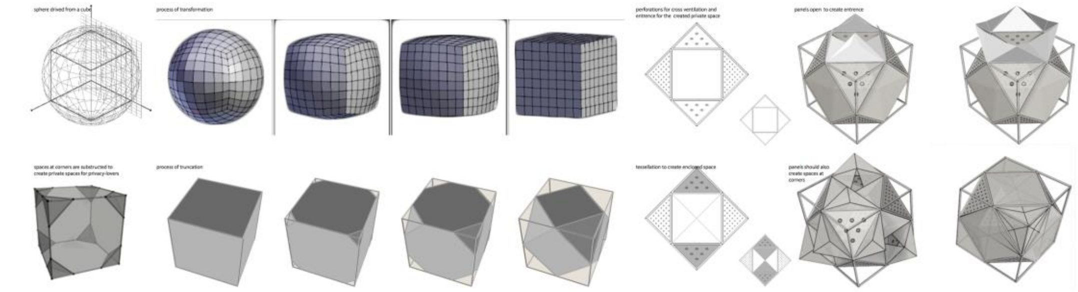

Figure 1. Initial Design of the Component

The design of the component is achieved in parametric environment as shown in Figure 2

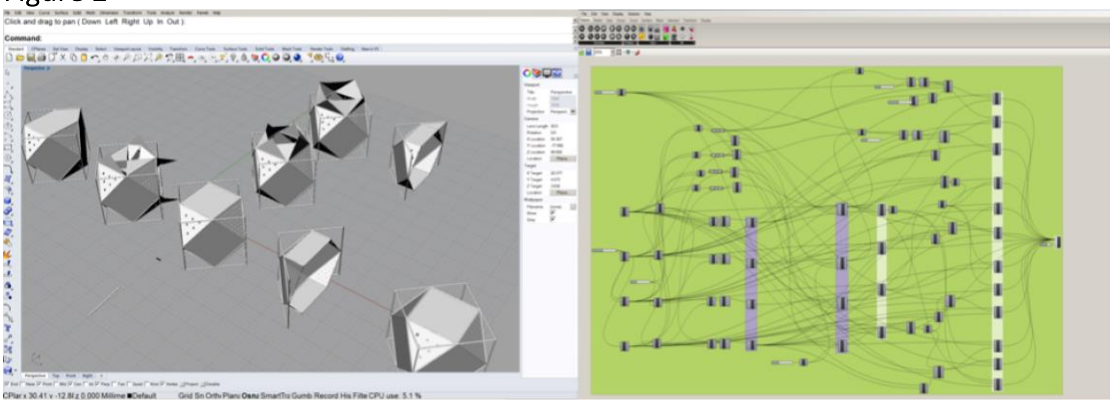

Figure 2. Parametric/Generative Model and the Resulting Component

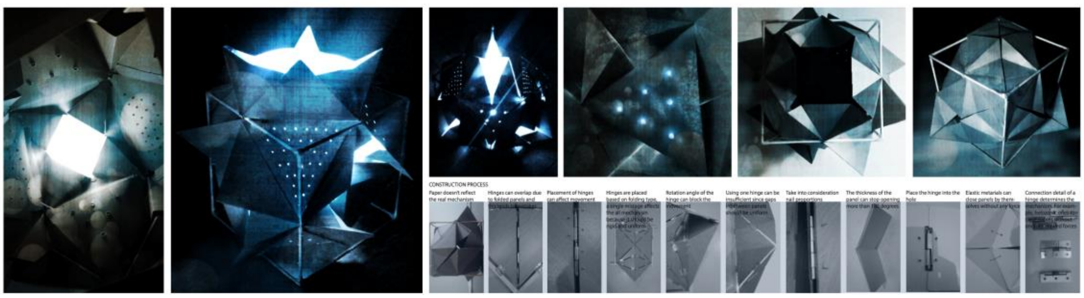

Figure 3. Final Component and the Details

There are two different modes of deployment in each surface responding the need and the ambient conditions. Surface materials and textures are also determined accordingly.
The prototype is shown in Figure 4.

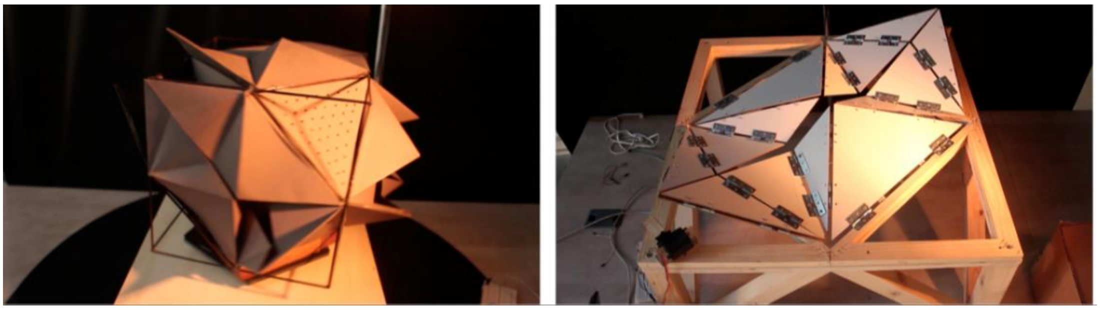

Figure 4. Working Prototype

Conclusion

The parametric modelling toolls and computational design approaches re-value origami in design. Particularly the design of responsive systems and their kinetic mechanisms can easily be deciphered by using origami which provides an invaluable medium of design analysis for complex deployable responsive structures.

Optimizing Unfoldings of Convex Polyhedra

Anna Lubiw
(The University of Waterloo, Canada)

It is an open problem whether every convex polyhedron has an edge unfolding, where we cut along its edges and unfold without overlap. However, if we allow cuts through faces there are a number of known unfoldings, in particular, the star and source unfoldings and several generalizations of them.

In this talk, I will survey the known unfolding methods and explore them from the perspective of optimizing various criteria:
- minimize the perimeter of the unfolding
- minimize the diameter or the bounding box of the unfolding
- maximize the minimum angle of the unfolding
- minimize the number of leaves of the cut tree of the unfolding (a zipper unfolding has two leaves)

The talk will include many open problems.

Applications of cut locus and Intuitive geometry --continuous flattening of polyhedra--

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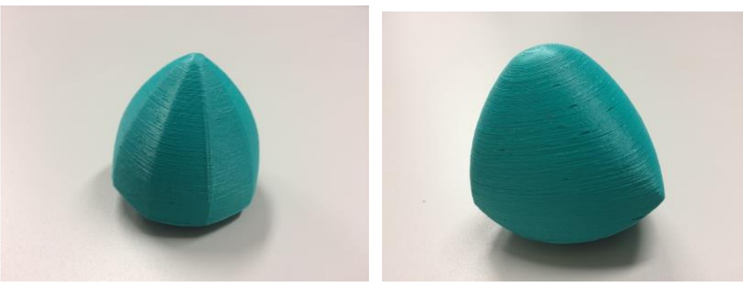
Cut locus is defined by Poincare in the beginning of 20 century, and studied long time in global differential geometry. In this talk, first we will review its history and recent results, a generalization of Jacobi's last statements and fractal cut locus, and discuss several applications (for example, shortest path problem, unfolding of polyhedron, continuous flattening of polyhedron).

Theorem (J.I., C.Nara & C.Vilcu). Every convex polyhedron has infinitely many continuous flat folding processes.

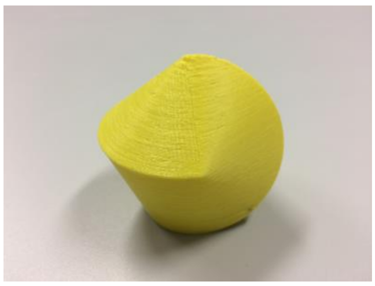
It is proved by using cut locus and Alexandrov'e glueing theorem.

Next we will show several problems of Intuitive Geometry. "Intuitive geometry" is the title of book written by Hilbert and Cohn-Vossen in the first half of 20 century. We will enjoy such kind of interestiong (amusing) geometric models made by 3D printer.

Continuous flattening of tetrahedron and cube made by thick panels



Surfaces of constant width



Rollable surface

Reference

[1] Jin-ichi Itoh, Chie Nara & Costin Vilcu, Continuous flattening of convex polyhedral, In: Comuputational Geometry, LNCS 7579, 85-97, Springer, 2012.

Rigid Foldability and Self Foldability

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Rigidly foldable origami structures are parallel mechanisms made of rigid plates and hinges, which is useful for the designs of deployable structures and self-folding systems in different scales. To design such transformable systems, we need to know if a given pattern forms a finite mechanism (rigid-foldability) and if the mechanism can be controlled to self-fold into desired states (self-foldability). Rigid-foldability and self-foldability have an inherent hardness, especially when dealing with the singularity and the degeneracy. However, lots of interesting behaviors of origami patterns come from these wicked cases; for example, bifurcation at the singular state of origami can lead to reprogrammable folding patterns, and the degenerate constraints yield overconstrained mechanisms with high stiffness and flexibility. The speaker talks about design methods to exploit such unusual behavior of origami patterns and to control the self-folding behavior of rigid origami.

Quaternion expression of the condition for rigid origami

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Abstract

The condition for rigid origami has been received significant interest from the standpoint of mathematics and engineering application. In the past research, the conditions that the combination of the motion velocities of dihedral angles $\dot{\rho}_i$ to be satisfied has been derived in consideration of the condition of a circuit around a vertex with n crease lines, a series of facet angles $\theta_{01}, \theta_{12}, \cdots, \theta_{n-1n}$ and dihedral angles $\rho_1, \rho_2, \cdots, \rho_n$ with using rotation matrix $\boldsymbol{\chi_i}$ as described in eq.(1).

$$\boldsymbol{\chi_n \chi_{n-1} \cdots \chi_1 = I} \tag{1}$$

In this study, the condition for rigid origami is derived by using a quaternion which can make effective expression of rotational operation. Use of the quaternion $\tilde{q}_i$ including the information of a series of unit vectors of crease lines $\boldsymbol{n_1}, \boldsymbol{n_2}, \cdots \boldsymbol{n_n}$ and dihedral angles $\rho_1, \rho_2, \cdots \rho_n$around a vertex make a possible to express the constraint condition of a circuit around a vertex as follows.

$$\tilde{q}_n \cdots \tilde{q}_2 \tilde{q}_1 \boldsymbol{r} \tilde{q}^*{}_1 \tilde{q}^*{}_2 \cdots \tilde{q}^*{}_n = \boldsymbol{r} \tag{2}$$

Here, $\tilde{q}_i = \left(\cos\frac{\rho_i}{2}, \boldsymbol{n_i} \sin\frac{\rho_i}{2}\right)$, $\tilde{q}_i^* = \left(\cos\frac{\rho_i}{2}, -\boldsymbol{n_i} \sin\frac{\rho_i}{2}\right)$ (3)

In consideration that every quaternions $\tilde{q}_i$ at the time t=t+dt also satisfy eq.(2), it can be expressed as follows.

$$\left(\tilde{q}_n(t) + \frac{d\tilde{q}_n}{dt}dt\right) \cdots \left(\tilde{q}_1(t) + \frac{d\tilde{q}_1}{dt}dt\right)$$

$$= \underbrace{\left(\tilde{q}_n(t) \cdots \tilde{q}_1(t)\right)}_{\text{(A)}} + \underbrace{\left(\frac{d\tilde{q}_n}{dt}\tilde{q}_{n-1}(t) \cdots \tilde{q}_1(t) + \tilde{q}_n(t)\frac{d\tilde{q}_{n-1}}{dt} \cdots \tilde{q}_1(t) + \cdots\right)}_{\text{(B)}} dt + o(\delta q^2) = (1, \boldsymbol{0}) \tag{4}$$

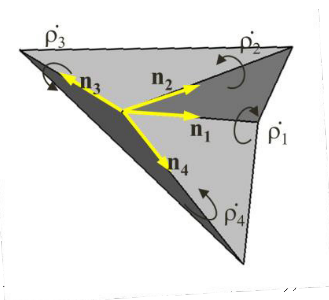
Since the term (A) is equal to (1,**0**), the term (B) is to be equal to (0,**0**).

About the term (B), by using derivative of $\tilde{q}_i$ with respect to ρ_i and $\boldsymbol{n}_i$ as shown in eq.(5), it can be derived the condition that the motion velocity of dihedral angles $\dot{\rho}_i$ and direction of crease lines $\dot{\boldsymbol{n}}_i$ should satisfy.

The result of the differentiation with respect to the variable ρ_i is described as shown eq.(6). This condition corresponds to the geometric characteristic that "the sum of the weighted fold line vectors is equal to zero."

$$\frac{d\tilde{q}_i}{dt} = \left(\frac{\partial \tilde{q}_i}{\partial \rho_i}\dot{\rho}_i + \frac{\partial \tilde{q}_i}{\partial \boldsymbol{n}_i}\dot{\boldsymbol{n}}_i\right) = \left(\boldsymbol{n_i}\dot{\rho}_i\tilde{q}_i + \left(0, \dot{\boldsymbol{n}}_i \sin\frac{\rho_i}{2}\right)\right) \tag{5}$$

$$\sum \boldsymbol{n_i}\dot{\rho}_i = \boldsymbol{0} \tag{6}$$



Reference

[1] W.Wu, Z.You, Modelling rigid origami with quaternions and dual quaternions, pp.2155-2174.

[2] N.Watanabe, K.Kawaguchi, The method for judging rigid foldability, Proc. 4th Int. Conf. on Origami in Science, Mathematics, and Education (4OSME), AK Peters (2006), pp. 165-174.

[3] T.Tachi, Simulation of rigid origami, Proc. 4th Int. Conf. on Origami in Science, Mathematics, and Education (4OSME), AK Peters (2006), pp. 175-187.

Bifurcation diagram of disk packings on logarithmic spirals

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[2]Research Institute for Electronic Science, Hokkaido University, Japan

1. Introduction

Van Iterson's bifurcation diagram for disk packings is a fundamental tool in the geometric study of spiral phyllotaxis. He studied the cylindrical model with linear lattices, the centric model in the plane, and a cusp model on the cone in 1907. The cylindrical model is popular recently, as it has PSL(2,Z) symmetry. It is known that the bifurcation diagram of disk packings on linear lattices is a dual graph of the bifurcation diagram of Voronoi tilings on the same linear lattices [1]. Here we show the duality between the bifurcation diagrams of disk packings and Voronoi tilings in the centric model, on logarithmic spiral lattices [2,3].

2. Bounded distance with multiplicative symmetry.

A logarithmic spiral lattice $\Lambda = \{z^j\}_{j \in Z}$ has a single generator $z \in C$. Fig.1 is an example with disk parastichy numbers 3, 5, and 8, where the dashed lines show the Voronoi tiling for Λ. In van Iterson's model, the radius of each disk $R|z^j|$ is proportional to $|z^j|$. Our result is that the coefficient R defines a bounded distance function in the plane, $d(z,w) = |z-w|/(|z|+|w|)$.

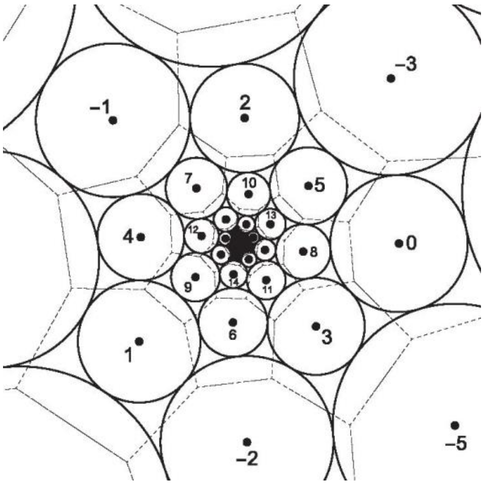

Fig.1 Disk packing and Voronoi tiling on a logarithmic spiral.

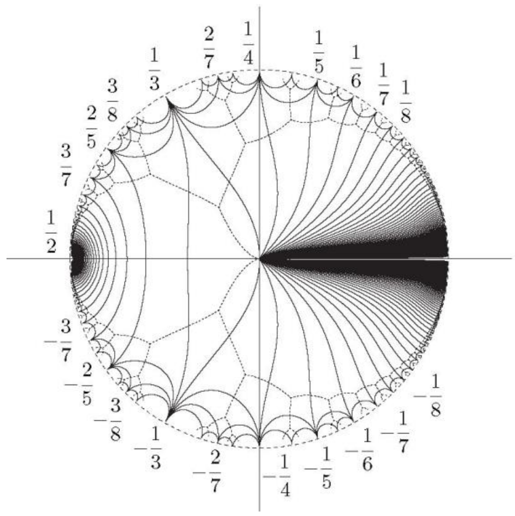

Fig.2 Bifurcation diagram of Voronoi tilings (dashed lines) and van Iterson's diagram

3. Disk parastichy number, Voronoi parastichy number, and continued fractions

In the phyllotaxis theory, the number of spirals is called a parastichy number. We show that the bifurcation of Voronoi tilings is written by an equation of the packing distance d. We show that, if the generator z is fixed, a disk parastichy number is also a Voronoi parastichy number. The continued fraction expansion of the divergence angle $\arg(z)/2\pi$ plays an important role in the proof. This gives the duality of the bifurcation digrams, and a rigorous proof that van Iterson's diagram in the centric model is connected and simply connected, with the Farey tree structure.

Reference

[1] Hellwig, H., and Neukirchner, T., Phyllotaxis, Die mathematische Beschreibung und Modellierung von Blattstellungsmustern, Mathematische Semesterberichte 57 (2010), 17-56.

[2]Yamagishi, Y., Sushida, T., and Hizume A., Voronoi spiral tilings, Nonlinearity 28 (2015) 1077-1102.

[3] Yamagishi, Y., and Sushida, T., Spiral disk packings, submitted.