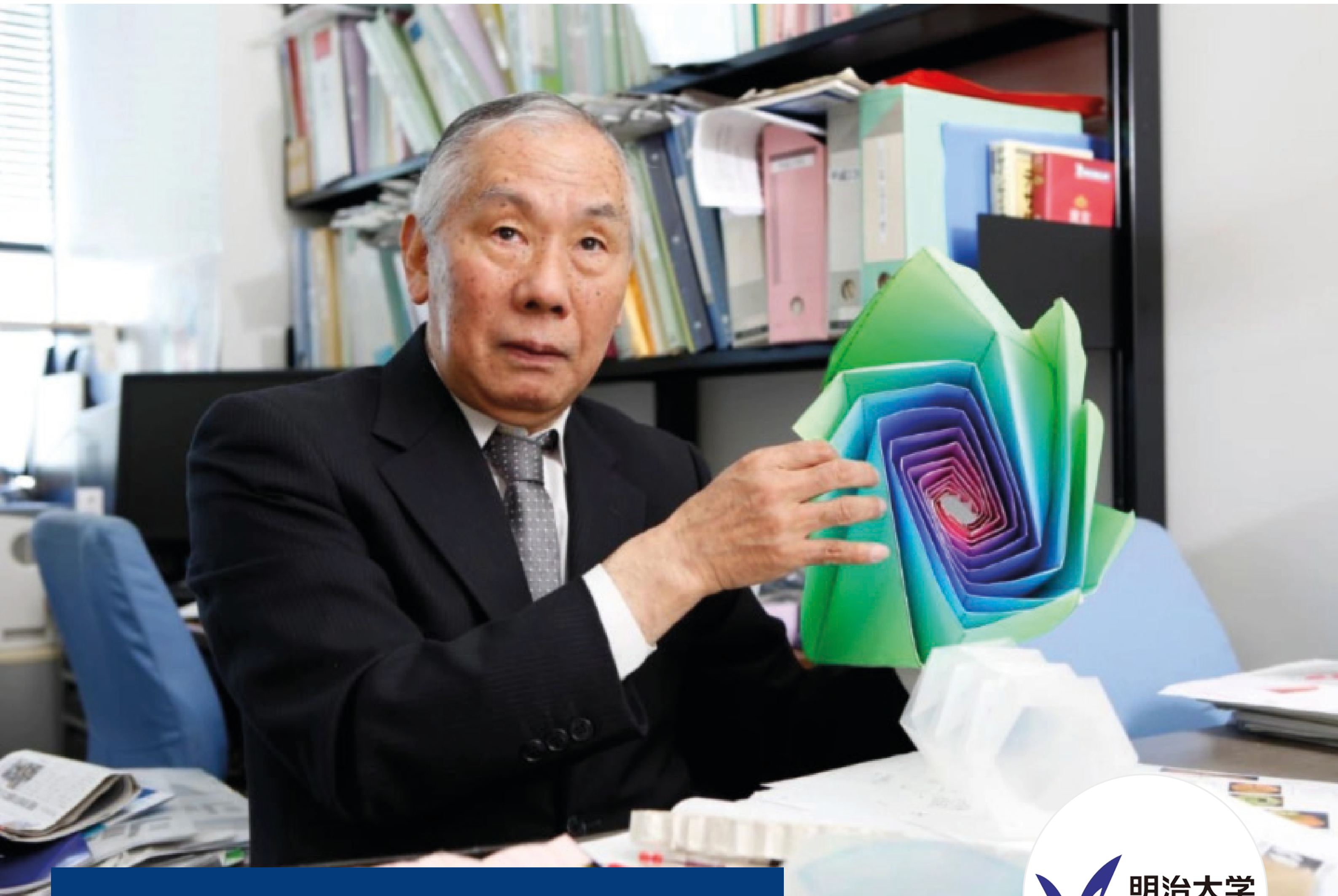

Origami Engineering: inspired by Japanese folding culture

Kirigami and fan folds represent new opportunities

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Origami, the Japanese art of transforming a single sheet of paper into various shapes, is a traditional cultural activity and form of play that children all over the world are familiar with. More recently, it has been adopted by international educational institutions as an tool to enhance thinking skills and concentration.

The artistic aspect of origami also attracts adults, and origami exhibitions are held in many countries around the world. More recently, the application of origami-inspired approaches to engineering have been attracting attention, since the structural characteristics of origami can be applied to industrial products and daily necessities.

However, while many people know about origami, few people have heard about origami engineering.

The history and industrialization of origami

Papyrus, the origin of the word paper, began to be used for paper in Egypt around 2500 BC. Since Egyptian and Western writing instruments were designed to scratch, the papyrus-based paper of the time had to be thicker and could not be folded. In Japan and China, on the other hand, brushes were used as writing tools, so the thinner the paper, the better.

Such paper for brushes was first invented in China, and these paper- and ink-making methods were introduced to Japan in AD 610. Later, other paper-making techniques developed independently in Japan, and the Japanese created the world's first foldable paper using tenacious elm. Subsequently, it was discovered that washi became more rigid and produced a beautiful lustre when folded.

During the Edo period (1603-1868), when Japan adopted a policy of national seclusion, paper became more popular, and a more playful form of origami to create animals such as cranes and turtles was developed. It was also during this period that the world's oldest book on origami was produced. Later, during World War II, a British engineer evolved and developed a method to mass-produce honeycomb origami, inspired by the Japanese Tanabata festival decorations. This was the beginning of the industrialization of origami. Industrial honeycomb, which has the highest axial rigidity for its weight, is now used in rockets and bullet trains and has become a multi-trillion-yen industry.

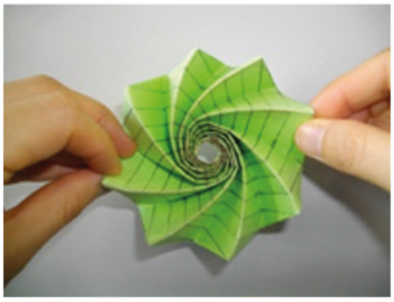
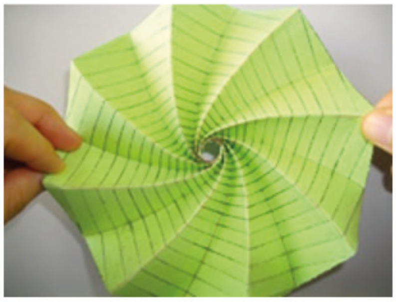
The birth of origami engineering and application of honeycomb

In Japan, where origami is a part of traditional culture, Dr. Taketoshi Nojima of Kyoto University proposed the concept of origami engineering to further apply its advantages to industrial applications. Currently, research on origami engineering is mainly promoted by the Origami Engineering Research Group of the Japanese Society for Applied Mathematics, which was established by Prof. Hagiwara.

One of these research undertakings is to improve the honeycomb structure. Conventional manufacturing methods were unable to produce curved-surface honeycombs. However, by applying traditional Japanese paper-cutting techniques (kirigami), three-dimensional curved honeycomb has been successfully manufactured. Furthermore, changes to the pattern of cuts and polygonal lines used, enables the creation of wing- and eave-shaped honeycombs.

Automobile interior parts generally have complex shapes. Conventional technology is rarely able to reproduce these complex components and, when it is possible, it is not easy to produce them as a continuum. However, by applying the kirigami honeycomb technology approach, it was found that the parts could be reproduced entirely in one piece. We have also succeeded in creating arbitrarily shaped structures with a single honeycomb using a state-of-the-art robot. We expect these discoveries to revolutionize design. This curved-surface honeycomb technology based on kirigami has had such a significant impact on industry that kirigami has also become an international term, alongside origami.

Courtesy of Kazuya Saito of Kyushu University

Courtesy of Meiji University

Industrial engineering aspects of origami engineering

There are three core aspects of origami engineering for industrial engineering, namely:

- the design and manufacture of origami structures that can expand and shrink;
- an effort to create an origami design for anything; and
- the design and manufacture of origami structures that are lightweight yet rigid.

Below, we explain these three approaches and provide examples.

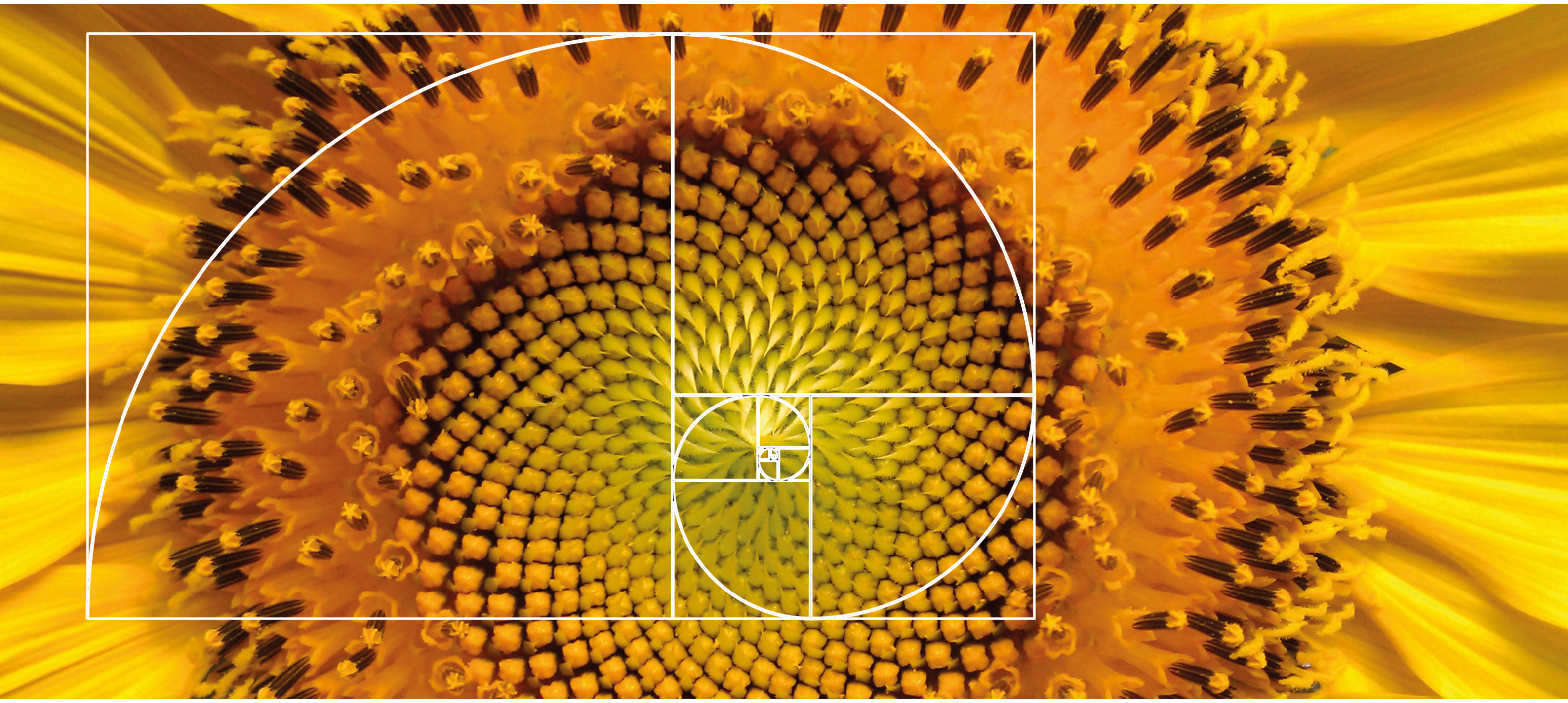
1) The design and manufacture of origami structures that expand and shrink (biomimetics origami)

Dr. Nojima, who first proposed origami engineering as mentioned earlier, also succeeded in making insects out of origami, thus creating a new field known as biomimetics origami. As indicated, biomimetics origami is inspired by the natural world. For instance, various insects are able to fold their wings very compactly, and these complex folding patterns can be drawn using elementary geometric rules and then reproduced using origami.

The origin of biomimetic origami began with the study of plants: many plants grow new parts at specific angles, thus creating a spiral pattern that consists of right- and left-handed equal-angle spirals. An example is the arrangement of the seeds of a sunflower. The number of loops in the spiral follows the Fibonacci sequence (where every number is the sum of the previous two numbers, i.e. 1,1,2,3,5,8, etc.).

The ratio of the adjacent numbers in the Fibonacci sequence gradually approach the golden ratio, which is the point at which the balance between the length and width of a rectangle form is most stable and aesthetically pleasing. Found abundantly in nature, the Fibonacci sequence has also been applied in historical buildings and works of art. This spiral arrangement can also be expressed in origami, an example of which, based on the arrangement of sunflower seeds, can be seen below.

Biomimetics origami also has industrial applications. Its structure has been used in the energy-absorbing materials for cars because of its excellent ability to absorb impact energy as gently as a cushion. When a conventional rectangular type of absorber is used, the initial



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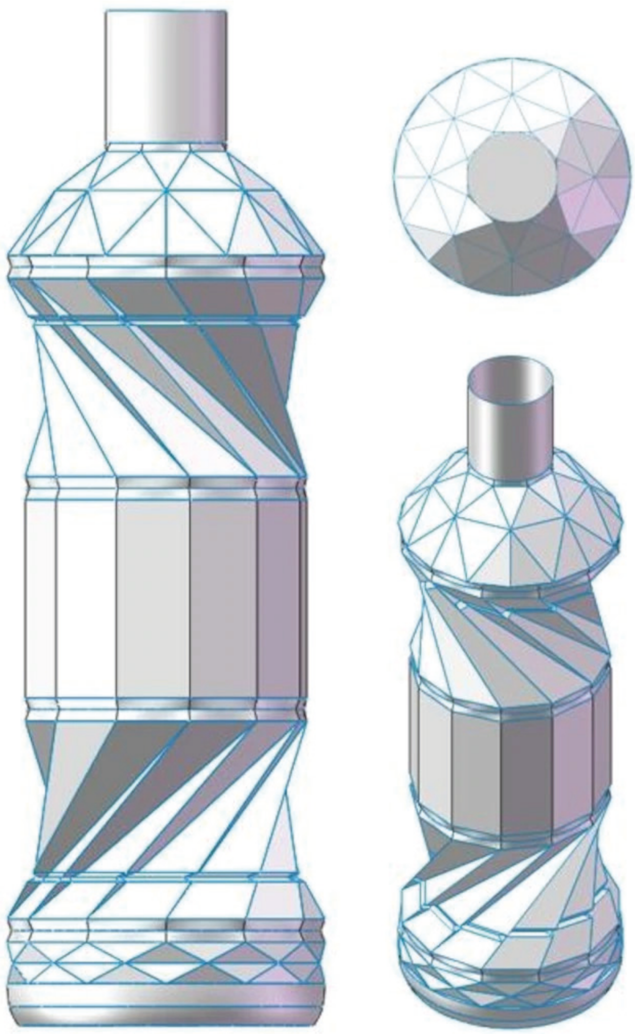


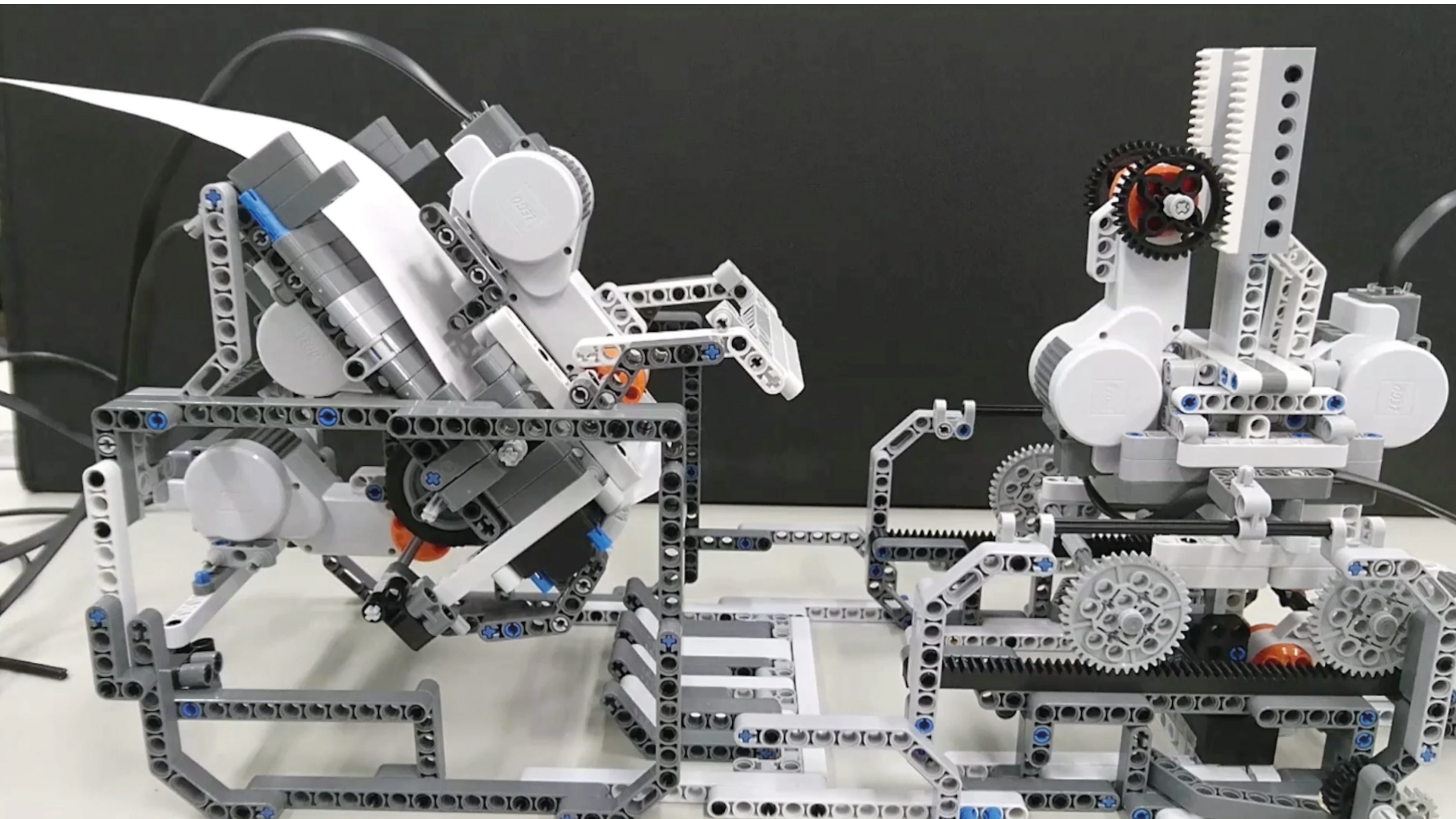
peak load is high, which can sometimes harm the occupants. With this type of absorber, the amount of deformation is only about 70% of its length. On the other hand, when an inverted spiral origami structure is used as an energy-absorbing material, the load value remains almost constant without changing with the deformation, while the amount of deformation reaches 90% of its length due to the characteristics of the origami folding. Consequently, research is now being conducted on the use of the new origami structure for absorbing materials that are able to absorb high impact energy, reduce the impact load, and that can be manufactured at a lower cost than the current structures.
Another application is plastic bottles. Today's PET bottles are designed to be foldable and small enough to be easily recycled, but it originally took ten years to achieve the commercialization of this product. At first, the foldable feature of the origami structures was able to be incorporated into the design, but then the unfolding feature, or spring-back, would occur, with the result that the bottle did not maintain its folded state and would return to its original height. The addition of grooves to accommodate the folded parts finally enabled us to create a PET bottle that can be folded easily and neatly and does not return to its original height.

The expandable and shrinkable characteristics of this origami structure are now also being researched and developed for use in other sectors, such as in space for solar panels for satellites and telescopes, and in the medical field, for stents to expand blood vessels from the inside, and for stomach-cleaning robots.

2) Creating an origami design for anything

Next, let's look at origami design, which attempts to make anything out of origami. It is a particular challenge to fold a complex polyhedral shape from a single sheet of paper without any gaps. To begin with we used reverse engineering, mainly used in manufacturing, to build a system that uses a photo of the product to create a development

Fig. 2 - 3D origami robot printers. ***Courtesy of Meiji University***



drawing with a glue allowance, and origami mountain and valley lines. Reverse engineering means working backwards in the design and manufacturing process to investigate the specifications and original manufacturing methods, operating principles, and blueprints. In practice, for instance, a point cloud is generated from the data of an actual vehicle or clay model; STL data is generated for conversion to CAD; and then a CAD or finite element method (FEM) model is generated for simulation to verify the part.

An Origami Geometry Calculation System is used to support reverse engineering. A real stuffed toy (seen here on the right of the picture) was formed into a laminated structure using a 3D printer, while the item on the left was made from paper using this Origami Geometry Calculation System and a 3D origami robot printer (see Fig. 2 below). This type of origami printer is currently being used in many sectors, including medicine, education, and urban development, for design support systems, daily necessities, and hobbies.

Courtesy of Meiji University

3) Design and manufacture of origami structures that are lightweight yet rigid

Origami structures can also be rigid in spite of their light weight. Inspired by the origami honeycomb, we created a space-filling model using tetrahedra and octahedra. The octahedral and tetrahedral halves create a spatial emphasis and, when they interlock, make a structure very strong.

These interlocking origami structures have been used commercially for solar cell panels and solar heliostats. Panels made by multi-stage press forming are 6～7 times stiffer than a conventional panel of the same weight and do not require additional reinforcement to maintain this flatness even for wide surfaces which tend to have weak rigidity. As the height of the cores is limited when constructing multiple cores from a single panel, the concept of the Assembly Core Truss Panel (ACTP), in which the cores are built and assembled one by one, was considered. For example, a paper core made of 24 hollow octahedral and 25 hollow tetrahedral interlocking halves can support a person weighing 60 kg.

Courtesy of Meiji University

The properties of these ACTPs can be applied to pentagonal and cubic octahedral semi-shapes, for example to create effective packaging materials for transporting foods such as strawberries and eggs, which are prone to breakage during transport, as well as for pluripotent stem cells or blood, which degrade easily during transport.

Origami is customarily made from paper; when using cardboard, plastic, or metal, however, one has to confront many issues, such as a lack of stability after folding and unfolding, difficulty in reproducing complex folds, and the challenge of manufacturing inexpensive objects while maintaining their original functions. Fortunately, modelling and numerical simulation techniques are now helping to solve these problems.

Digital reproduction of a fan

Finally, we should mention the folding fan, unique to Japan. Fans were used to repel insects and to start fires, and were created almost simultaneously around the world. At that time, fans were still made to be flat fans. However, the Japanese applied their folding culture to fans, too, allowing them to be folded. The three-dimensional folding fan, made of Japanese paper and bamboo sticks or "bones", originated in Japan during the Heian period (AD 794-1185) and subsequently spread all over the world.
In the Edo period (1603-1868), fans were painted by famous painters such as Sotatsu Tawaraya, Hokusai Katsushika, Korin Ogata. Their paintings were compositions that integrated the bamboo bones into a three-dimensional shape that was most effective when made into a fan.

Here, we present a case study of a digital fan that reveals this fact mathematically. The surface of the fan is distorted in various ways. The rate of contraction above and below the arc are due to the length of the fan bones that hold the arc in place. The fan model was created by approximating the distorted surface as a plane.

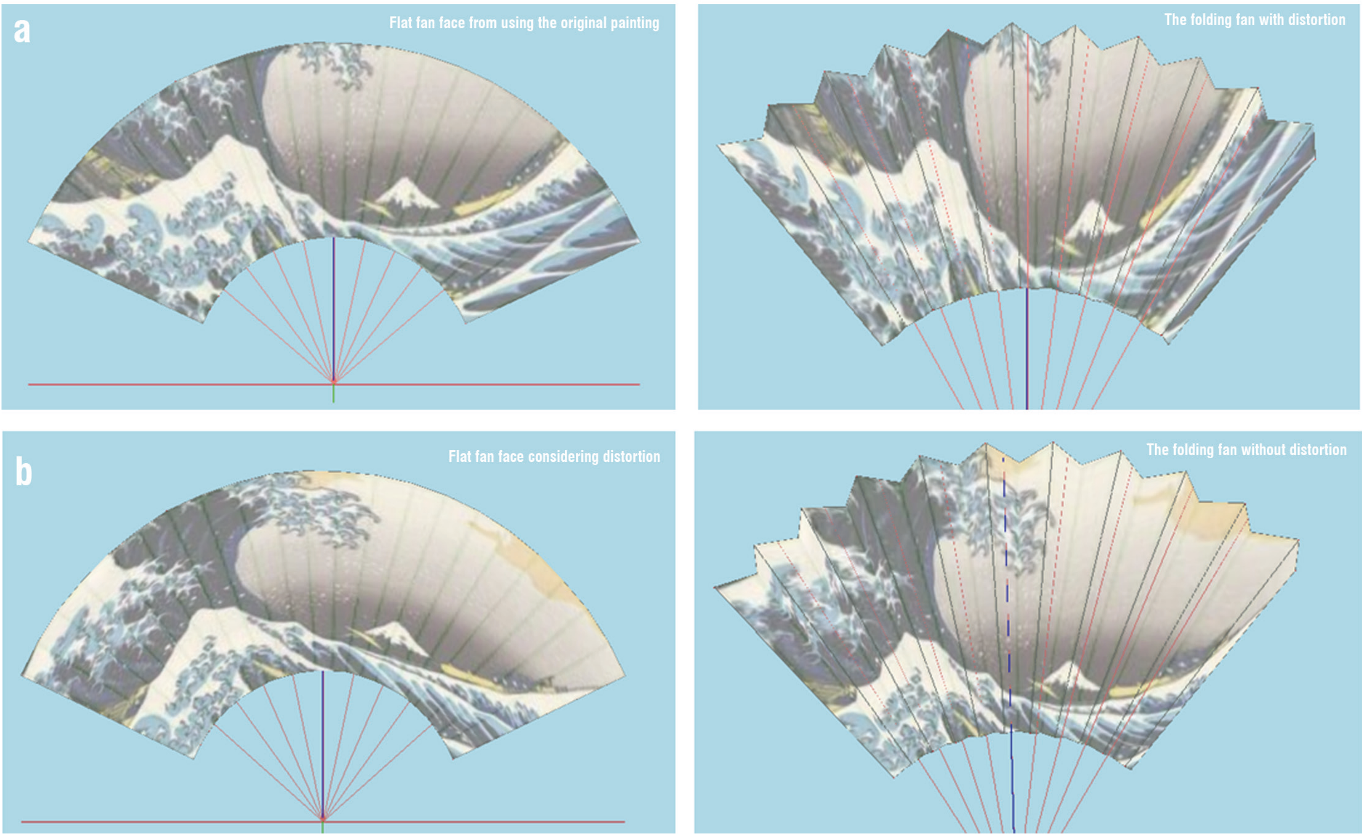


Fig. 3 - a) The original drawing is cut out as it is and is made into a fan; b) the original drawing is adapted for the finished fan using the digital fan program. Courtesy of Meiji University

We then applied ourselves to the challenge of rendering one of Hokusai Katsushika's Ukiyo-e "36 Views of Mount Fuji" (The Great Wave off Kanagawa) as a fan painting using the digital fan. Firstly, we cut out a part of this Ukiyo-e to make a fan shape. As shown in Fig. 3a, the distortion of the image is more pronounced, especially in the case of a long-boned fan. In the case of a short-boned fan, the distortion was less pronounced and it looked pleasant, but not good enough for an artistic work. Therefore, we used the digital fan program mentioned earlier to mathematically illustrate what is overlooked in a general sense.

We applied a fan template with the fan bones extended, in which the surface image was noticeably distorted when tailored to the Ukiyo-e. The program reverse-engineered the image to obtain the original fan image. In this case, when viewed as a plane, Mt. Fuji has "fallen sideways" and the wave shapes have been stretched horizontally, creating a completely different impression to the original painting (Fig. 3b, left). However, when folded to the planned size, the original Ukiyo-e appears on the surface of the three-dimensional fan. The difference can be clearly seen when comparing it with the distorted fan made earlier.

The motivation for the mathematical description of these digital fans is the tendency for Japanese folding fans of historical value to be preserved in flat form, with their bones removed, in wall paintings and hanging scrolls. This detracts from the value of the skilful drawing of the Edo-period painters and the three-dimensional artistic expression created from them. We wish to emphasize, therefore, the importance of maintaining and complementing the original three-dimensional form of these Japanese fans on display all over the world. This will reveal their value as a three-dimensional art form, which has been overlooked so far and will lead to the succession and development of traditional art forms.

Conclusion

It is now 20 years since the advent of origami engineering. Thanks to its light weight and high rigidity, as well as its ability to expand and shrink, there has been a great deal of interest in applying the results of origami engineering research to products. The wide range of applications that have already been realized suggests that origami engineering will grow as an essential technology in industry. Just as 3D additive printing has influenced design and manufacturing, origami engineering has the potential to revolutionize the way we design. At the same time, the mathematical thinking of origami engineering can help to preserve and pass on long-established cultural traditions.

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