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INTER-ACTIVE DESIGN

Towards a Responsive Environment

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Architected Morphing Matter: The Confluence of Geometry and Hidden Forces

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Matter is not always static; matter can morph. Cells divide, leaves grow, octopuses transform, robots reconfigure, bread rises, and pasta swells. Once we start to observe the physical world through a lens with temporal and spatial dimensions, we see a morphing reality.

Morphing Matter is an interplay of geometry and hidden forces. To compute, design, and fabricate morphing mechanisms that leverage both geometrical and physical knowledge of materials, we need to unfold the marriage of geometry and forces such as a conformal map of interconnected beams shrinking and fighting for the lowest entropy, a frustum-shaped groove with interfering disks swelling at differential diffusion rates, and a triangulated filler path affecting spacer fabric deforming with biased shear forces. Novel morphing mechanisms and applications like self-assembling furniture, crawling soft robots, and morphing pasta also materialise due to this marriage.

In a Disk

The visualisation of these hidden forces is the expression of the morphing potential. We can specify and visualise how these forces can be encoded into materials in a numerical simulation environment. For instance, in the environment, the shades of colour could represent the variations of deformation potential (An et al., 2018).

In 4D printed shape memory plastics, the printed material sample visually appears to be a flat and uniform white sheet. However, the hidden forces – that is, the residual stresses in the polymer chain – vary highly from one location to another. Here, stress is a mechanical term, indicating the force per unit. With the application of heat, the sheet will release all the hidden forces and self-fold to form a prescribed three-dimensional shape, such as a rose flower.

How can structures such as this rose flower be created? To do so, plastic is melted during an extrusion-based printing process, and its polymer chain is straightened and forced to lock in a less energy-preferred state. This process causes the generation of residual stress. Although the stress is hidden, energy stimuli such as the application of extra heat will release this residual stress, and the straightened polymer chains will return to their original wavy and random spaghetti-like configuration. The microscale rearrangement of the polymer chain exhibits shrinkage of the plastic sheet on a macro scale.

Notice that in this process, the direction of the residual stress always follows the printing direction. Therefore, if we push the limits of geometrical complexity even further, a flat disk can turn into the shape of a face, one of the most complex non-zero Gaussian curvature surfaces that are often used to validate the complexity of shapes a graphical algorithm can compute (Gu et al., 2020).

To fabricate continually extruded melted thermoplastics, a continuous printing tool path (i.e. a linear and directional hidden force field) has to be generated. Imagine we place equidistant black dots and tape non-stretchable

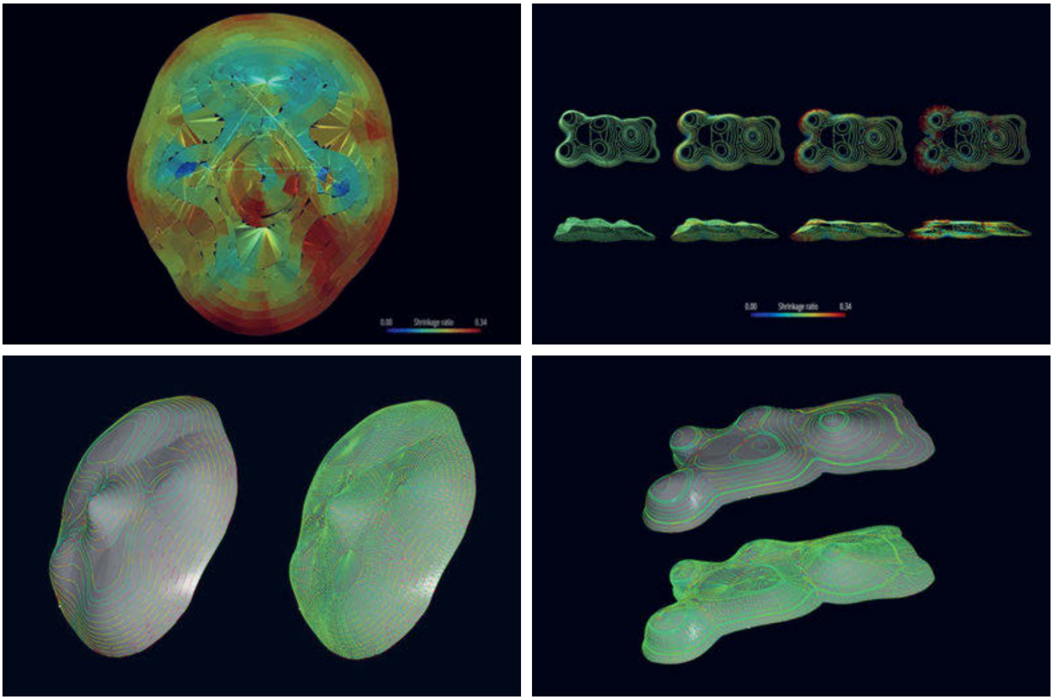


Fig. 1 *Thermorph*. 2018. The shape memory material utilises residual stress built into thermoplastic to self-fold a rose flower from a flat sheet. The colour gradient indicates the extent of residual stresses. Developed by Byoungkwon An, Ye Tao, et al. at Morphing Matter Lab, CMU. The numerical simulation was conducted by Xiaoxiao Zhang and Teng Zhang at Syracuse University.

Fig. 2 Geodesy Plus, flattening a face, developed by Jianzhe Gu et al. at Morphing Matter Lab, CMU.

thin strips along the radius of a three-dimensional face mask. To find its flattened layout, we can heat and soften the mask, press it uniformly against a plane, and spread any wrinkles. During the flattening process, the dots will move farther apart along the azimuthal direction, which is the amount of expansion. On the other hand, the expansion ratio indicates the required shrinkage that can turn the flat disk to the face. An inverse method inspired by this observation was built.

Beneath a Groove

Morphing structures are not always engineered with hidden forces introduced into a flat sheet by structural anisotropy or compositional heterogeneity. A simple and universal diffusion-based mechanism can also enable a transient morphing effect in structures with parametric surface grooves (Tao et al., 2021). A surface groove is a pure geometrical factor, which can be realised easily with a single material and fabricated using low-cost manufacturing methods (e.g. stamping, moulding, and casting). The hidden forces are induced by a differential diffusion (swelling) rate.

A multiphysics simulation that takes mechanical property changes and diffusion into account verified that parametric surface grooving could induce temporary asynchronous swelling or deswelling and transform flat objects into designed, three-dimensional shapes. Kinetic swelling modelling at the level of individual grooves confirms that a delayed response to stimuli (exposure to a solvent or air) for the centre of protrusions compared to other regions (e.g. top or bottom of the surface exposed) causes asymmetrical morphing of the object. By tuning the grooving pattern, we can achieve zero (e.g. helices) and non-zero (e.g. saddles) Gaussian curvature geometries.

Suppose we purposely seek the geometry and hidden forces in this morphing mechanism. In that case, the width, gap between, and height of surface grooves are the geometrical factors; and the diffusion of liquid into the solid material which induces kinetic energy is the hidden force that causes the morphing.

This mechanism is suitable for materials that can swell in water or organic solvents. It is practical to create these structures from a single material such as food gels. Grooving patterns in food gels can improve the efficiency of specific food manufacturing processes and facilitate sustainable food packaging. For instance, morphing pasta with groove patterns can be flat-packed to reduce air space in the packaging. Apart from food, this method can be adapted to morph elastomers, like elastic resin and silicone in organic solvents.

Between Beads

When we lay spherical beads on an inert substrate, the unique interplay and interactions between the expanding beads and substrate can be leveraged to make the structure self-morph. Hydrogels are polymers that can absorb 10–1,000 times their weight or volume of water or aqueous fluids. When hydrogel beads are adhered to a flexible substrate such as paper or cloth and immersed in water, the beads expand by absorbing the water, causing the substrate to bend and transform a flat substrate sheet into a volumetric form (Jain et al., 2021). Here, the bead expansion is the hidden force, and the layout of the beads and the outline of the substrate are the geometrical factors.

By placing the beads at a measured distance from each other, we can control the bending angle of the substrate. The closer the beads are to each other, the more dramatic the bending is (i.e. a higher bending curvature). Many exciting shapes and transformations can be explored by placing beads at a uniform distance, variable distance, or on both sides of the substrate – thus making hydrogel beads and a flexible substrate of choice a very versatile material combination.

Creating most shape-changing interfaces requires advanced material synthesis, specialised lab settings for fabrication, and technical knowledge to simulate their morphing behaviour. Moreover, the cost of procuring the materials is very high. These factors become a barrier for makers who want to create and replicate such structures. On the other hand, this beads-on-substrate technique is low cost, the materials are readily available, and the design space to explore new geometries such as branching and *kirigami* is vast, with many applications to the real world.

For instance, expanding beads on substrates with kirigami or branching patterns can mimic underwater plants, and more robust forms of these can be used for coral conservation efforts. To create advanced designs and push the limits of democratising this technique even further, a computational tool was made to design and simulate the morphing behaviour of the structures.

Entangled Threads

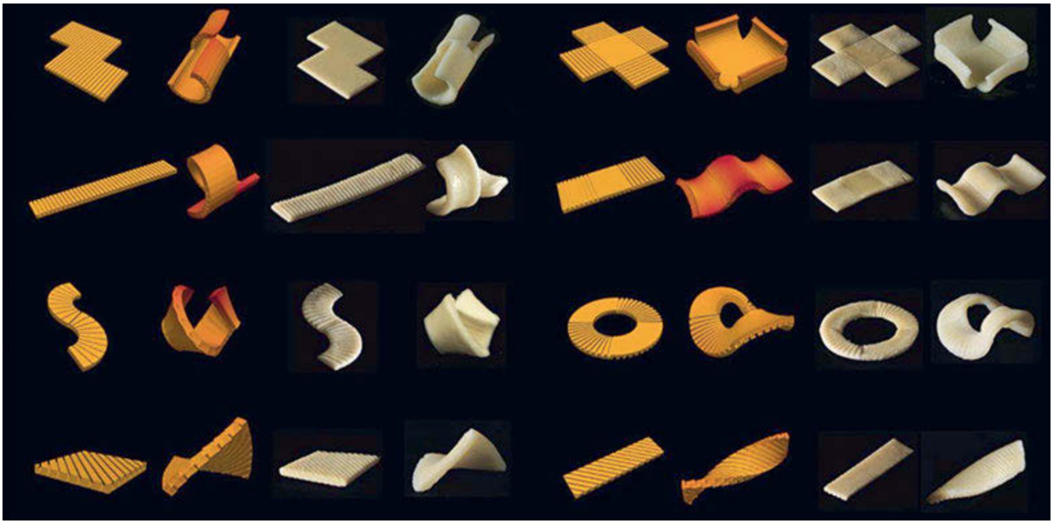
Spacer fabrics are a category of knit structures that have a unique springy feel, breathability, and low density, making them useful for various applications such as uppers of running shoes and padding for orthotics. Using weft knitting, we can tune the production parameters of the fabric directly on a stitch-by-stitch basis, incorporating multiple functional characteristics in a given object.

We think of spacer fabrics as a type of mechanical metamaterials – an aggregate material where the designed microstructure influences the overall properties. A particularly relevant metamaterial is “bristles” – hair-like structures with a high aspect ratio suited to transmit and amplify deformations. We explore bristles as a variant of spacer fabrics in which one face layer is unravelled after knitting with directionally biased actuations (Albaugh et al., 2021).

Spacer fabrics can have a slight but noticeable mechanical bias in the vertical direction (i.e. under pressure, the material will tend to shear in the same direction). This bias can be produced by altering the order in which the face fabrics are formed near the filler row. The face which is knit first will tend to shear downward. The bias can be minimised by alternating between the face-knitting order, and the opposite bias can be introduced after a gap of face rows without filler rows joining them.

Our “bristle” structure is formed the same way as the spacer fabric, but one face is unravelled after knitting. The resulting structure is very similar to a “plush” or “terry” knit but with much longer loops than are typically produced in these processes. Knitting a sacrificial face helps ensure that the bristles are appropriately formed; without it, the monofilament may not drop cleanly off the needles after each row. The most predictable results are achieved if the “sacrificial” unravelled face was knit in the same kind of yarn as the remaining one.

Inspired by kirigami-clad pneumatic mechanisms, we applied a biased bristle skin to a fibre-reinforced elastomeric



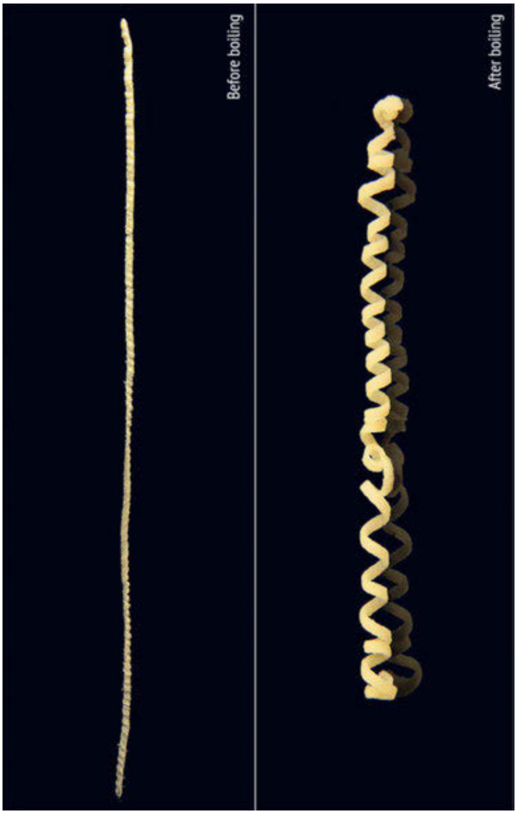


Fig. 3 Experiments and numerical simulation of morphing food, developed by Ye Tao, et al. at Morphing Matter Lab, CMU, and Teng Zhang, et al. at Syracuse University.

Fig. 4 Experiments and numerical simulation of morphing food, developed by Ye Tao, et al. at Morphing Matter Lab, CMU.

Fig. 5 Morphing silicone triggered by an organic solvent, developed by Ye Tao, et al. at Morphing Matter Lab, CMU.

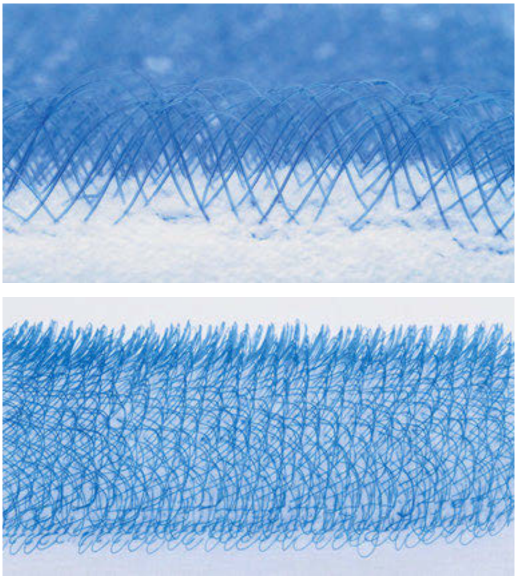
extension actuator. When the actuator is pressurised, it stretches uniformly; when it is allowed to relax, the bristle structure acts as a ratchet and keeps the front part of the actuator in place while the back slides forward. As a result, a “caterpillar” robot formed, which is soft and lightweight.

Nature or Culture, Surviving or Living

Now that we know how matter morphs, let us situate ourselves in the challenges of today – climate disasters and human exploitation of the earth – and reflect on the implications of morphing matter.

The current global sustainability challenge is primarily induced by how we make, grow and consume physical things. Technological advances in many areas are required to tackle it, aside from coordinating with policy and industry. Our lab, Morphing Matter Lab at Carnegie Mellon University,[1] needs to contribute to this global effort, and we believe our accumulated expertise in designing morphing materials may amplify this effort.

Many morphing materials studied in our lab are inspired by how natural seedpods morph and deliver seeds by harvesting environmental energies, including moisture gradient and temperature fluctuation. However, unlike electromagnetic systems – the dominant machines for “motion” in autonomous and robotic systems of today – our morphing material systems are often triggered by electricity-free energy stimuli, yet programmed to be adaptive and responsive, such as a soil sensor that can self-drill into the ground triggered by the rain.



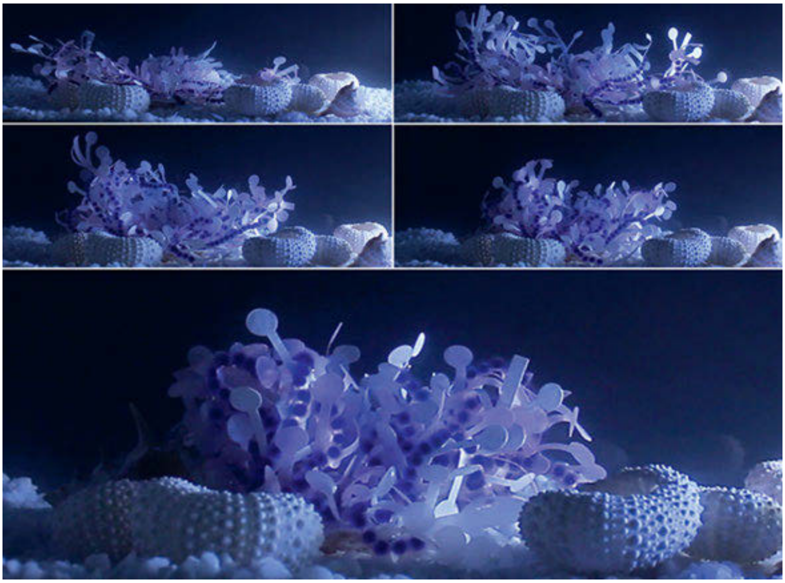


Fig. 6 Gradual rise and sideward bending of a kirigami artefact, developed by Harshika Jain, Kexin Lu, et al. at Morphing Matter Lab, CMU.

Fig. 7 Knitted bristles with directional bias, developed by Lea Albaugh, et al. at CMU.

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[1] Morphing Matter Lab: https://www.morphingmatter.cs.cmu.edu/.

The morphing mechanisms introduced earlier uncover many bioinspired morphing systems with creative design practices and can contribute to the global sustainability effort with innovative yet sustainable products:

- 4D printing for sustainable manufacturing and on-site self-assembly. We have demonstrated that our 4D printing technique could potentially cut 7/8 of the additive manufacturing time. In addition, the self-folding behaviours can save assembly efforts and remove additional joint assembly so the system can be easily recycled.

- Morphing food for sustainable packaging and cooking. Flat-packed food with engineered geometry and optimised surface area can save shipping space, shorten cooking time and reduce carbon emissions.

- Self-drilling and biodegradable payload carriers can be leveraged for soil sensor deployment in agriculture and wildland.

In the journey of developing sustainable ways of living, do we ask people to stop buying new clothes and wear uniforms every day because we need to be sustainable? Do we ask people to eat flat spaghetti only because other three-dimensional shapes of pasta consume more packaging space and produce more plastic waste? Do we ask people to stop eating chocolate because a cocoa tree replaces national forests in Africa for commercial benefits? Do we ask people to stop eating steak and seafood since tofu is also protein-rich but much more environmentally friendly? The answer is likely no. The styles of wearing, eating, and living represent our culture, legacy, and identity as human beings. Along with thinking of climate change and our present and future, we are constantly striving for a balance; a balance between nature and culture, surviving and living. For us, we cannot miss the opportunity to celebrate human-centred morphing matter, nor to reflect on its very existence at the same time. We have just started to construct, compute, and contextualise sustainable morphing matter.

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