Programmable matter by folding

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Programmable matter is a material whose properties can be programmed to achieve specific shapes or stiffnesses upon command. This concept requires constituent elements to interact and rearrange intelligently in order to meet the goal. This paper considers achieving programmable sheet shapes that can form themselves in different shapes autonomously by folding. Past approaches to creating transforming machines have been limited by the small feature sizes, the large number of components, and the associated complexity of communication among the units. We seek to mitigate these difficulties through the unique concept of self-folding origami with universal crease patterns. This approach exploits a single sheet composed of interconnected triangular sections. The sheet is able to fold into a set of predetermined shapes using embedded actuation. To implement this self-folding origami concept, we have developed a scalable end-to-end planning and fabrication process. Given a set of desired objects, the system computes an optimized design for a single sheet and multiple controllers to achieve each of the desired objects. The material, called programmable matter by folding, is an example of a system capable of achieving multiple shapes for multiple functions.

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There are several issues that increase the gaps between theory and practice. First, the theory provides an algorithm to design a folding of any three-dimensional voxel shape, but can be inefficient in its required sheet resolution. In practice, we find that human origamists can often design more efficient foldings from a given-resolution sheet. Second, the theory assumes that the sheet has zero thickness, while real materials have positive thickness. Thickness is an issue mainly for compound folds, where one folds multiple layers of material at once, which we resolve by using stretchable material for crease joints. Third, the theory assumes that the sheet can flex during the motion to a folded state, while the material we use is relatively stiff to simplify control. Fourth, the theory also assumes continuous control—that the entire sheet can be completely controlled in an arbitrary fashion—while digital control necessitates discrete control with a finite number of actuators and uncertainty. Nonetheless, we show that reliable discrete controllers exist and can be computed for the practical shapes we consider.

Process
To create a self-folding smart sheet, we have developed a two-step process of planning and fabrication. The planning process begins with a set of goal configurations. After completion, it returns a plan of the optimized location and control sequence of creases that must be folded to create such configurations. The second step is the fabrication process which takes this specific plan and produces a working sheet. This process is depicted in Fig. 2.

Planning Algorithms. The planning process consists of four distinct algorithms: the input to the process is one or more folded states of a common box-pleat grid, which can be computed by the universality algorithm of ref. 18 or designed by human origamists. The output is a design of a programmable matter sheet and controllers for folding that sheet into any of the input shapes.

The first planning algorithm unfolds each of the given shapes. This algorithm is based on a rigid origami simulator which is able to fold a shape given a set of creases. We apply the simulator in reverse to heuristically unfold a given three-dimensional folded state, by applying local unfolding forces at the creases. Upon success, the simulator returns a continuous path for each tile during unfolding.

The second algorithm takes in the continuous folding paths from the first algorithm and produces a discrete folding plan. This plan includes which creases must fold, in which direction, and at what time in the folding process. The algorithm discretizes the given continuous motion into discrete time intervals called phases. Creases belonging to a common phase are all folded simultaneously. The first and second algorithms are run sequentially for each one of the goal shapes, producing an individual discrete plan for each goal shape. For example, if three goal shapes are desired, these algorithms will produce three plans for three separate sheets, each able to fold into one of the goal shapes.

The development of the programmable material first uses planning algorithms to plan a single shape, then merges multiple plans for multiple shapes, and finally outputs a design for how to fabricate the components of the sheet.
The third algorithm receives each of the individual plans from the second algorithm and assembles them onto one sheet. Then the algorithm takes all creases that need to be folded from all the incoming plans and divides them into groups. These groups are created such that every phase from the incoming plans can be written as a linear combination of the new groups. That is, activating one or more of the groups created by the third algorithm can create the first, second, third, etc. phase from the plan for the first shape, as well as the first, second, third, etc. phase for the second goal shape, and so on. This algorithm is run once for each possible arrangement of individual plans from the second algorithm on a single sheet. For example, if there are two goal shapes and the second algorithm returns two corresponding plans, then these two plans can fit simultaneously on a single square sheet in eight different arrangements (four 90° rotations and one 180° flip).

Finally, the fourth algorithm chooses the optimum arrangement from the output of the third algorithm to minimize either the number of actuators or number of actuator groups. We either minimize the number of actuators to save energy and fabrication time, or minimize the number of groups of actuators to eliminate unnecessary circuitry and minimize folding time by maximizing parallelism. Finally, we check for detrimental antagonistic overlaps which can cause incorrect folding. An antagonistic overlap requires a crease to bend one way for one shape and the opposite way for a second shape. Bidirectional actuation is possible in practice but brings added mechanical complexity, which we avoid with the simple unidirectional actuators described as part of the fabrication process. Therefore, we remove the actuator from such a crease to allow passive motion caused by the folding of other creases. Often we find that the folding of other creases correctly folds the passive crease, both in simulation and in practice; otherwise, we call the passive crease detrimental. Any arrangement with a detrimental antagonistic overlap is discarded.

The running time of the last three algorithms is polynomial for a fixed number of target shapes. For a large number of shapes, we would have to replace the exhaustive search over all arrangements of individual plans on a sheet. The running time of the first algorithm has not been analyzed, but its similarity to the gradient flow of ref. 21 suggests that a pseudopolynomial time bound holds.

Fabrication Process. The second step of our process is the fabrication of the three components of the programmable material: the tiled composite sheet, thin-foil actuators, and flexible electronics. The first component, the sheet, must have semirigid tiles to transfer motion and are easily embedded within the tiling. We use thin (100 μm) foil Nitinol shape memory alloy (SMA) for the actuator material. The planform geometry is formed with a pulsed ultra-violet laser micromachining system. The micromachined foil is tinned, fixed in a jig to hold a desired (folded) shape, and annealed at 420°C for 30 min. This annealing process resets the undeformed martensitic state such that when unfolded, the actuator will “remember” its folded shape when heated above its transition temperature of 70°C (24). Thus any fold that is annealed into SMA can be manually flattened, and upon actuation, the fold is reformed. There are four folds in each actuator: one central bending fold, and three distal clamping folds. For assembly onto the sheet, we open all four folds (Fig. 3, top). The actuator is placed onto the sheet with each of the three legs inserting into a through-hole. The distal bends are heated with an external source, causing them to close (Fig. 3, middle). This results in a heat-activated staple, which tightly grips the substrate (Fig. 1, A, B). When the central fold is heated, the actuator folds tightly closed, which is the source of folding actuation for the sheet (Fig. 3, bottom). These actuators only remember folds in one direction (i.e., they fold from 0°–180°). We have also prototyped antagonistic (bidirectional) actuators, however, for the algorithms and shapes discussed in this paper, only unidirectional actuators are needed. Thus, to minimize undesired complexity and maximize fabrication efficiency, only unidirectional actuation is described.

The third component of programmable matter is the stretchable electronics, which are capable of bridging the elastomer flexure creases. It is essential that the electrical traces can not only bend while the tiles are folding, but also stretch to achieve compound folds. This presents a significant challenge which is not achievable with standard flexible circuits. As a solution, we pattern the trace with a series of cuts, or a mesh, that allows the metal to lengthen as needed (Fig. 1C). The meshes are micromachined from a sheet of copper-laminated polyimide in the exact pattern needed and bonded to the surface of the tiling. The actuators are soldered to the traces forming groups of actuators, as determined by the planning algorithm, to form a single power circuit. Thus to fold a shape, current is applied through one or more groups, heating all actuators in this phase through Joule heating until folds are complete and magnets engage. Then a second set of groups, or phase, is activated, a third, etc.

Programming. An important aspect of creating programmable matter is the actual programming that allows a user to trigger the formation of the desired shape. For the self-folding sheet, we developed a method for programming shapes by stickers. The idea is to enable users to request the formation of a shape without the use of a computer. The intuition is to create the smart sheets to include all the electronic circuitry except for actuator and connector wiring. Stickers are thin materials that contain the circuitry required to connect and trigger the correct actuators for making a specific object. If we have k objects that are achievable from a base sheet, the user will receive the base sheet and k stickers, each of which programs the formation of one of the k

* A compound fold is a fold that creases two or more layers of the sheet at once. These multiple layers are created through previous folds, see Fig. 1F.
Thus, programming the object reduces to placing the stickers on top of the sheet. Sticker Programming has three components: Programmable Matter with Sticker Operating System, Sticker Compiler, and Programmed Sticker device. Algorithms with the same flavor as the ones described for designing the placement of the actuators and the control for creating an object are used to automatically design the base sheet and the stickers that go with it.

Results
Using the two-step planning and fabrication process described above, we have designed, fabricated, and tested a thirty-two-tile sheet, with twenty actuators, five actuator groupings (Groups 1–5), three phases (Phase A–C), and two goal shapes (“boat” and “airplane”). This design is optimized to use the minimum number of actuators, 14.4% fewer than nonoptimized arrangements. Upon activating Groups 1, 2, and 3 the nine actuators of Phase A are heated, and the “boat” folds (Fig. 4A–D). Once unfolded by hand, Groups 2 and 4 are activated, and Phase B (the triangular flaps) of a “paper airplane” folds (Fig. 5A–C). Finally, Groups 3 and 5 receive current, and Phase C, the second phase of the “airplane” (backbone and wings), folds (Fig. 5D–F) (See also Movie S1). One amp is run through the actuators, each with a resistance of 0.25 Ω, resulting in 1–2.25 W of power depending on the phase. Each phase takes between 6 and 10 s to fold, requiring between 6 and 22.5 Joules of energy for activation. Speed can be increased, but at the expense of a higher power input.

Discussion and Conclusion
With the concept of self-folding origami, we hope to bring programmable matter into reality in the near future. We have presented an end-to-end approach to creating self-folding sheets capable of realizing multiple shapes. In theory, our algorithms can plan the creation of any three-dimensional shape. In practice, we are limited by actuator size and torque considerations, as well as control and coordination constraints for multiple actuators.

At the moment, the self-folding devices we have created are limited to a finite set of shapes that can be created with one-way actuators. This limitation is primarily due to the physical realization of the sheet (one-way actuators, fixed wiring scheme, etc.), which is specified by the algorithm given the desired shapes. This limitation could be alleviated in one of two ways: (i) bidirectional actuation at each joint, each individually addressable by the controller or (ii) calculation of a large number of mutually compatible basis shapes from which goal shapes could be composed. The former would involve only the first two steps of the algorithm (the third and fourth are required to place multiple goal shapes in a predetermined manner on a single sheet). The latter is a natural extension of our current methods but with larger sheets with more actuation. The result would be a single sheet that can be folded into any shape up to a prescribed resolution.

One important consideration for the practicality of this method is the scalability of the self-folding sheet, both in terms of resolution of the individual elements (tiles) and the number of elements that can be effectively combined in a single sheet. First, the resolution of the tiles is limited by the scalability of each element. The current materials and methods use to create the substrate can be reasonably shrunk to create tiles on the order of a few millimeters in largest dimension. Below this threshold, lithography and micromolding techniques (for example, molding elastomers using capillary action (25)) could be used to reduce feature sizes further. Scaling of actuation has two considerations:
fabrication and performance. For fabrication, similar actuators could be reduced to millimeter feature sizes (26) using current methods or submillimeter scales using physical vapor deposition and patterning (27). For these actuator types, Joule heating becomes more effective at smaller scales, bandwidth will increase (mechanically as well as thermodynamically), and the energy density should remain constant. However, there are other potential actuation modes for smaller scales including pneumatic, electrostatic, and a variety of electroactive polymers (ionic and dielectric).

We have shown that the gaps between theory and practice can be surmounted for the shapes we have considered. Nonetheless the gaps suggest additional theory that would be interesting to develop if possible. For example, can we quantify the flexibility of the material needed by motions of an unfolded sheet into target folded states? The area of rigid origami, which forbids flexing except at creases, is relatively underdeveloped, making this a challenging question. For a given resolution, we could also study whether it is always possible to reach a folded state without unfolding any folds, which would provide theoretical backing for potential wells.

Nevertheless, the current results suggest very promising applications. We can create a bulk material that is preprogrammed to adopt several shapes. Reconfigurable devices are an immediate application. Examples include a measuring cup system that folds to hold any amount from a quarter teaspoon to multiple cups, a shelving system that folds to fit a user-defined space with a user-defined number and type of divisions, and a puckering sheet that provides tactile feedback for displaying information to the blind or people in the dark. A wider range of devices could be incorporated to make a “Swiss army knife” of sorts, able to form a tripod, wrench, antenna, or splint. In the future, finer resolution and larger sheet sizes will become available as our manufacturing techniques evolve.

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Fig. 5. Flat sheet prior to folding (A). Four-actuator group controlling flaps activated (B). Magnets for the first fold engaged (C). Remaining actuators are activated (D). Final shape (E) and inverted (F).


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