SOFT ROBOTICS

REVIEWS

Design, fabrication and control of origami robots

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Abstract | Origami robots are created using folding processes, which provide a simple approach to fabricating a wide range of robot morphologies. Inspired by biological systems, engineers have started to explore origami folding in combination with smart material actuators to enable intrinsic actuation as a means to decouple design from fabrication complexity. The built-in crease structure of origami bodies has the potential to yield compliance and exhibit many soft body properties. Conventional fabrication of robots is generally a bottom-up assembly process with multiple low-level steps for creating subsystems that include manual operations and often multiple iterations. By contrast, natural systems achieve elegant designs and complex functionalities using top-down parallel transformation approaches such as folding. Folding in nature creates a wide spectrum of complex morpho-functional structures such as proteins and intestines and enables the development of structures such as flowers, leaves and insect wings. Inspired by nature, engineers have started to explore folding powered by embedded smart material actuators to create origami robots. The design and fabrication of origami robots exploits top-down, parallel transformation approaches to achieve elegant designs and complex functionalities. In this Review, we first introduce the concept of origami robotics and then highlight advances in design principles, fabrication methods, actuation, smart materials and control algorithms. Applications of origami robots for a variety of devices are investigated, and future directions of the field are discussed, examining both challenges and opportunities.

Origami, from ori meaning folding and kami meaning paper, denotes the ancient Japanese art of paper folding. In engineering, origami is associated with folding processes in which a structure is created from a sequence of spatially organized folds, similar to an umbrella. Origami fabrication is an important design principle in nature[1]. For example, leaves and flowers of many plants are folded within the bud, insect wings often exhibit a folded morphology inside the cocoons and carapaces[2], and the function of many proteins is dependent on the way they fold from chains of amino acids[3]. The concept of origami can also be explored as a design tool in engineering. Starting with a single sheet of paper or even a linear string, complex 3D objects with distinct mechanical properties can be constructed by folding. Therefore, concepts borrowed from the ancient art of origami and from nature can be applied to create a new class of robots called origami robots. Origami robots are autonomous machines, whose morphology and function are created by folding. Their bodies are made of many dynamic folds that act together to actuate the machine. The prototypical origami robot is made of a single planar sheet that is folded into a complex 3D morphology. Origami robots have built-in compliance because of the geometry of the folds and the creases in the material, and they are semi-soft, that is, they exhibit the properties of both rigid and soft robots[4]. At the same time, rigid structures and spatial linkage mechanisms can be created owing to the tiling structure and origami folding pattern[5].

The origami approach to making robots can be considered a top-down approach. This is in contrast to the conventional bottom-up approach for making robots, that is, independent components such as nuts and bolts are manually assembled in an incremental way, requiring time, effort and expertise. Origami robots provide an opportunity to simplify and accelerate the design and fabrication of robots. Manufacturing currently relies on creating a complex infrastructure of fixtures and rigs specific for each manufactured structure that cannot be easily adapted for other structures. Fabricating structures in a plane and then folding them into their final shape enables the quick and efficient creation, prototyping, testing and refinement of complex designs. This approach also makes manufacturing more flexible through enabling fast reconfiguration of production lines, without the need for precise alignments of rigid fixtures. Although improvements in machining and 3D

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printing technologies have automated some aspects of manufacturing of mechanical structures, these methods are still costly and time consuming compared with planar fabrication techniques (for example, photolithography, laser machining, planar printing and pick-and-place assembly).

Origami-inspired manufacturing has the potential to enable unprecedented rapid fabrication and customization of robots. Using folding, unfolding and new foldings, origami robots can adapt their shape to specific tasks and environments, and achieve agility of motion. The origami approach to robots promises a simplified method for the design and fabrication of complex mechanisms. Furthermore, origami robots have several advantages compared with traditional systems, including the ability to achieve improved autonomous locomotion, manipulation and performance by morphing the shape of their bodies, by actuating continuously along their bodies and by deforming to adapt their bodies to the task and environment (for example, a folded wheel that can become smaller for tighter turns[6]). Moreover, they can adjust their compliance from rigid to soft. There are key hardware and control challenges and opportunities for creating origami machines that achieve their full potential. Origami machines can be fabricated from a variety of materials (for example, plastics, metal, paper, rice paper and sausage casing). An origami machine starts as a planar composite material with tilings and creases and requires the integration of sensors, actuators and computation. Origami machines also require algorithms to support their design, fabrication and control. Recent advances in the universality of computation are making it possible to automate the design of any static origami shape. Rapid prototyping and additive manufacturing can be leveraged for fast manufacturing with minimal manual assembly steps. Advances in motion planning are enabling control methods for creating a 3D system from a planar sheet, as well as algorithms for task execution.

What is an origami robot?

The body of an origami robot includes all subcomponents of a robotic system, that is, actuation, sensing, computation and power. Origami robots are fabricated from a flat composite sheet and can implement self-assembly, shape change, locomotion, manipulation or a combination of these tasks through folding (FIG. 1). The flat sheet consists of tilings separated by compliant joints, forming a crease structure. Typically, folding occurs at defined compliant joints, whereas the rest of the sheet is rigid. A subclass of origami structures that allows internal cuttings in the initial sheet is called Kirigami.

To form a desired 3D shape, the sheet undergoes a sequence of folding steps. This process requires a plan for when in the sequence each edge should be folded and to what angle. For assembly, additional (embedded) mechanisms may lock the structure into place to hold the new 3D shape without consuming energy. Origami robots may require power and computation laced throughout the sheet along with embedded actuation and sensing. Actuation may be associated with individual joints and/or the body as a whole. Once fabricated, an origami robot requires low-level control to move and higher-level planning and control algorithms to achieve its intended capabilities in the world, for example, to pick up an object or to move to patrol a street. Because origami robot bodies may contain many folds, their actuation may require the parallel and coordinated movement of subsets of these folds. The built-in folds are design features that enable degrees of freedom and compliance for the origami mechanism. Controlling these degrees of freedom requires new approaches to planning and control.

In this Review, we discuss important developments in origami robotics in the context of design, modelling, fabrication, actuation, sensing and control, and highlight applications and areas with great potential for societal impact.

Design and modelling

Folding enables a broad range of possible shapes for origami robots. The first algorithmic approaches to computational origami design were demonstrated in 1996 (REF.[7]), and a variety of different computational protocols have since been developed[8–11].

Universality of folding. An important question in computational origami design is that of universality, that is, whether it is possible to fold any geometric shape starting from a single square sheet of paper. The first proposed algorithm addressing universality determined the sequence required to fold a single square of paper into a planar origami shape that takes the (scaled) shape of any connected polygonal region, even if it has holes[12]. The algorithm produces a theoretically universal solution; however, the solution may be too inefficient to be usable in practice because the solution wastes material and generates many layers of folds. An alternative practical algorithm with universality guarantees that every convex face is folded seamlessly, starting as one unfolded convex polygon. This work provides the theoretical underpinnings for the Origamizer algorithm and software package[6].

Algorithms for computational origami design. The input to an origami algorithm is an origami sheet and its crease pattern (FIG. 2). A crease pattern is an origami diagram that consists of the creases of the final model[11]. The number of results in the algorithm[9,13–16] defines the range of shapes achievable by folding a sheet of a particular geometry with a specified crease structure. A commonly used crease pattern is the box pleat. In a box-pleat pattern, the grid of allowable creases in the sheet constitutes a square lattice together with the diagonals of each square (forming right triangles, FIG. 2a). This grid enables the sheet to fold into a variety of objects that could form the basis for bodies, legs or grippers, even at fairly small resolutions at the centimetre scale (FIG. 2b). A strip of material with such a crease pattern can efficiently fold into arbitrary surfaces with a few layers of material[16].

The key challenge in computational origami design is to develop an algorithm that defines the best way to create a specific 3D shape by folding (FIG. 2c). Here, 'best' can refer to different objectives, including minimizing the size of the origami sheet, the number of folds or the need

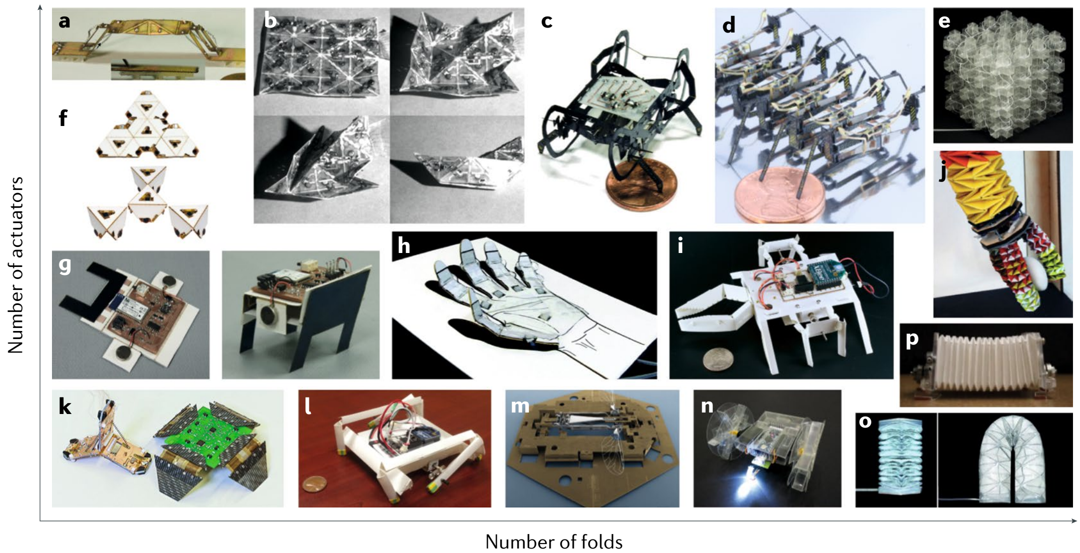

Fig. 1 | **Diversity of origami robots.** Origami robots arranged by the number of folds in the device and the number of actuators (note that the axes are not to scale). Inchworm-inspired crawling robot[90] (part **a**), programmable universal sheet[86] (part **b**), quadrupedal microrobot[83] (part **c**), myriapod-inspired microrobot[84] (part **d**), transformable metamaterial[76] (part **e**), self-folding swarm robot[71] (part **f**), self-assembling pop-up stick-slip locomotion robot[72] (part **g**), distributed pneumatic actuation of folds[74] (part **h**), print and fold mobile manipulator[68] (part **i**), manipulator based on twisted-tower origami pattern[140] (part **j**), low-profile robotic origami with integrated sensing[82,141] (part **k**), foldable hexapedal robot[69] (part **l**), monolithically fabricated pop-up flying insect robot and support structure[61] (part **m**), print and fold wheeled robot[26] (part **n**), pneumatically actuated paper–elastomer composite[77] (part **o**) and crawling robot driven by multistable origami[63] (part **p**). Panel **a** is reproduced with permission from REF.[90], Institute of Electrical and Electronics Engineers. Panel **b** is reproduced with permission from REF.[86], Proceedings of the National Academy of Sciences. Panel **c** is reproduced from Baisch, A. T. et al. High speed locomotion for a quadrupedal microrobot. *The International Journal of Robotics* **33** (8), 1063–1082 (2014), SAGE Publishing, https://doi.org/10.1177/0278364914521473 (REF.[83]). Panel **d** image courtesy of Robert Wood, Harvard University Boston, US. Panel **e** is reproduced from REF.[76], CC-BY-4.0. Panel **f** is reproduced with permission from REF.[71], Institute of Electrical and Electronics Engineers. Panel **g** is reproduced with permission from REF.[72], Institute of Electrical and Electronics Engineers. Panel **h** is reprinted with permission from SOFT ROBOTICS 2015, pp. 59–70, by Niiyama et al., published by Mary Ann Liebert, Inc., New Rochelle, NY. Panel **i** is reproduced with permission from REF.[68], Institute of Electrical and Electronics Engineers. Panel **j** is reproduced with permission from Jeong, D. et al. Design and analysis of an origami based three-finger manipulator, *Journal of Mechanisms and Robotics* **7** (2), 021009 (REF.[140]). Panel **k** is reproduced with permission from École polytechnique fédérale de Lausanne. Panel **l** is republished with permission of The American Society of Mechanical Engineers, from Hierarchical kinematic design of foldable hexapedal locomotion platforms, Faal, S. G. et al., **8**, 011005 (2016) (REF.[69]); permission conveyed through Copyright Clearance Center, Inc. Panel **m** is reproduced with permission from REF.[61], IOP Publishing. Panel **n** is republished with permission of The American Society of Mechanical Engineers, from Integrated codesign of printable robots, Mehta, A et al., **7**, 021015 (2015) (REF.[26]); permission conveyed through Copyright Clearance Center, Inc. Panel **o** is reproduced with permission from REF.[77], John Wiley and Sons. Panel **p** is reproduced with permission from REF.[63], IOP Publishing.

for multiple folds, or providing flexibility regarding the initial sheet geometry. The tree method[7,13,17] determines the efficient folding of a square of paper into a shape with an orthogonal projection equal to a scaled copy of a given metric tree. 'Efficient' refers to a polynomial time algorithm (except for the first step, which places disks and rivers to reserve paper for flaps). This method works well in practice and is the foundation of most modern origami designs. However, algorithmic optimization is non-deterministic polynomial-time (NP)-hard[18]. This computational challenge can be addressed by identifying sub-classes of origami problems, by introducing approximate methods or by defining heuristics. For example, the strip method[19] finds the folding pattern of a given piece of paper into a scaled copy of any desired polyhedral complex (any connected union of polygons in 3D). However, this method does not provide a way to optimize the scale factor, causing inefficient paper usage.

It has been suggested that any polyhedral surface can be folded from a sufficiently large square of paper and that the folding can be computed in polynomial time[19]. Thus, a large enough printed sheet patterned with a specific crease pattern is capable of achieving any specific polyhedron. However, every desired shape might require a different crease pattern. An $n \times n$ box-pleat tiling can fold into any polyhedral surface consisting of $O(n)$ unit cubes on the cubic lattice[16]. Another result guarantees that any such folded state can be reached by a continuous folding motion without the material penetrating itself[14]. Therefore, exponentially many foldings can be created out of a single tiled crease pattern. By applying a standard voxelization procedure, any polyhedral surface or solid can be approximated on the cubic lattice. Thus, box-pleat tiling is a universal crease pattern that can fold into any polyhedral surface of a specified resolution. This theory suggests the formation of a regular pattern of potential

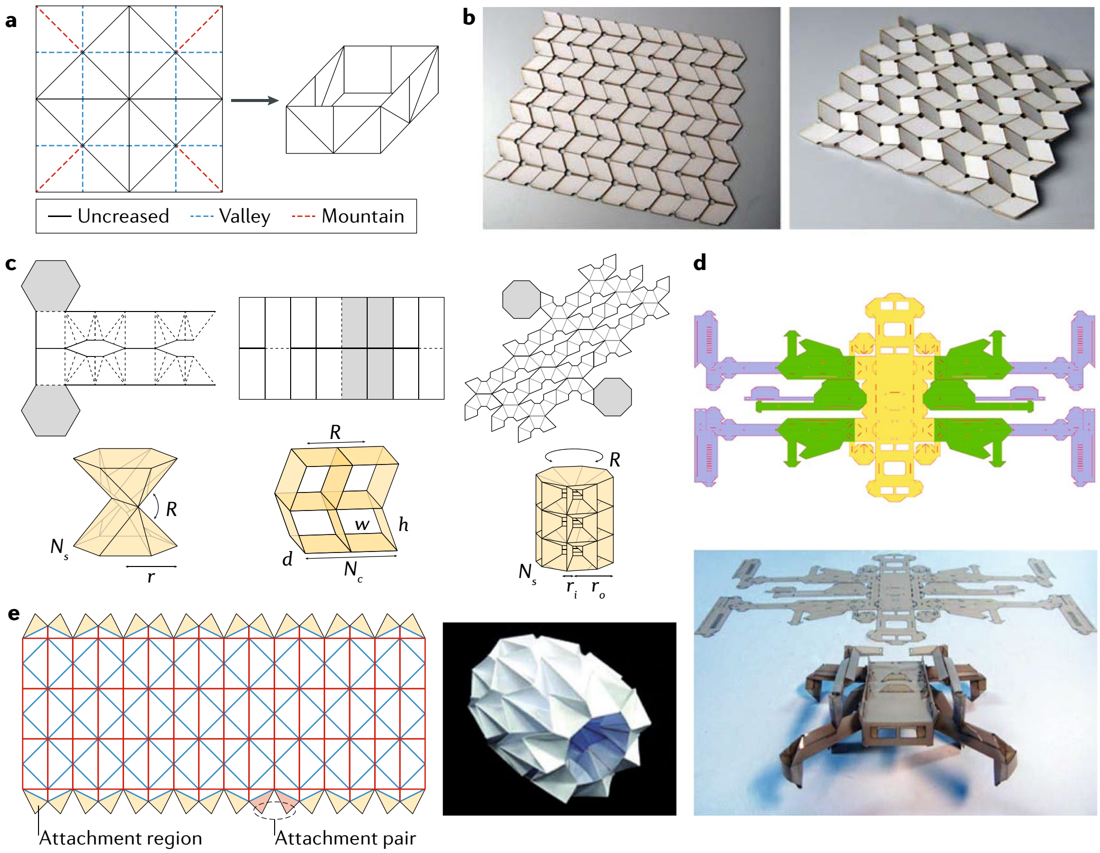

Fig. 2 | **Origami crease patterns for robotic components. a** | The box-pleat pattern consists of a square lattice with diagonal creases. This pattern can be used to create any given shape with voxel resolution at the size of the box. As an example, a set of mountain and valley folds (red and blue dashed lines) is shown that cause the flat sheet to fold into a rectangular bowl. **b** | The Miura-ori fold pattern (left) is a single degree of freedom tessellated origami fold pattern that can be folded (right) for the efficient packing and deployment of solar panels for spacecrafts[79]. For example, this pattern can be implemented in a self-folded shape memory composite[92]. **c** | Three basic joint types of origami robots. Hinge (left), prismatic (centre) and pivot (right) joints. **d** | Flat (top) and folded (bottom) versions of the body of a legged robot folded from a single sheet, including all mechanical components of the body (yellow), legs (green) and transmission (purple). **e** | 3 × 8 array of a waterbomb origami pattern with bridge and attachment regions used to form a morphing wheel[5]. *d*, diameter; *h*, height; N_c, number of columns; N_s, number of sides; *R*, range of motion; *r*, radius; r_i, inner radius; r_o, outer radius; *w*, width. Panel **a** is reproduced with permission from An, B. et al. Planning to fold multiple objects from a single self-folding sheet. *Robotica* **29** (1), 87–102 REF.[119]. Panel **b** is reproduced with permission from REF.[92], IOP Publishing. Panel **c** is republished with permission of The American Society of Mechanical Engineers, from Foldable joints for foldable robots, Sung, C. et al., **7**, 021012 (2015) (REF.[123]); permission conveyed through Copyright Clearance Center, Inc. Panel **d** is reproduced with permission from Michael Tolley (tolley@eng.ucsd.edu). Panel **e** is reproduced with permission from REF.[5], the publisher for this copyrighted material is Mary Ann Liebert, Inc. publishers.

wells in a way that the potential energy reaches a local minimum as the crease becomes completely folded. If the face of each triangle in the box-pleat pattern is attracted to the face of each of its three neighbours, then any combination of folds will result in attraction and thus a local potential energy minimum.

Computationally aided design. Despite the availability of theoretical algorithms, the practical realization of origami-based systems remains challenging. Even for rigid origami structures (that is, bending occurs only along defined folds), commercial computer-aided design (CAD) tools are not well suited because origami mechanisms often contain more degrees of freedom than those of the mechanisms typically modelled using CAD software, demanding complex kinematic equations, which slow the software. Moreover, currently available software applications do not contain synthesis tools to automate or simplify the design of origami systems. Recent research has sought to address these limitations (FIG. 3). The Origamizer software, for example, allows designers to explore a wide range of origami models and to generate the fold patterns required to generate a given 3D shape[20–22] (FIG. 3a). Other work has used topology optimization to generate folding patterns with desired, target geometric properties[23].

The software tool popupCAD enables the design of laminate composites that include structural, flexible and actuation layers for the engineering of origami robots and devices[24,25] (FIG. 3b). Continuing research efforts seek to simplify the design of print and fold origami robots through recursive combination from a library of parts[26] and through data-driven approaches[27]. Computationally efficient methods to predict the nonlinear mechanics of

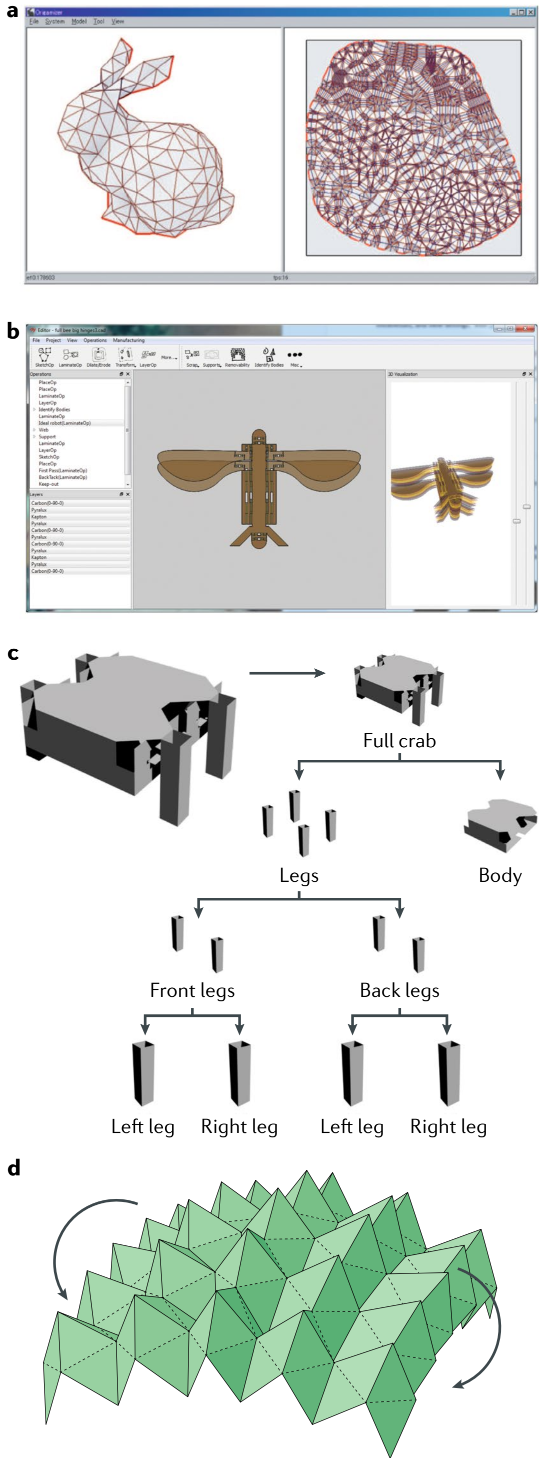

Fig. 3 | **Software tools for origami robot design. a** | The software tool Origamizer automatically generates fold patterns for a defined 3D shape[20–22]. **b** | The software tool popupCAD simplifies the design of multilayer laminates used to fabricate origami robots[24,25]. **c** | The Robot Compiler software automates the design of print and fold robots based on functional specifications[26]. **d** | Visualization obtained using the Merlin software that models the folding of non-rigid origami[28]. Panel **a** is reproduced with permission from REF.[22], Institute of Electrical and Electronics Engineers. Panel **b** image courtesy of Daniel M. Aukes, Arizona State University, US. Panel **d** image courtesy of Glaucio H. Paulino, Georgia Institute of Technology, US.

non-rigid origami structures have been implemented in the software Merlin[28] (FIG. 3d). Other software tools are also being developed for the design and simulation of the folding of inflatable mechanisms[29].

Current research has contributed software tools that aid the co-design of integrated mechanical, electrical and computational components of an origami robot. The origami robot compiler generates designs based on functional specifications, which are then fabricated as flat structures, folded, manually assembled and controlled through a smartphone app[30] (FIG. 3c). Recently, an interactive design tool called Robogami was introduced for the design of functional origami robots, ranging from the centimetre to the metre scale[31]. The electromechanical substrates of these robots are automatically designed. A searchable database of parameterized designs allows the user to construct 3D objects by hierarchically composing components from the database. These objects are then automatically unfolded in the software. Once a design is chosen, the simulation software can check whether it meets specifications such as stability, speed or payload. For example, an existing Robogami design for a crawling robot can be composed with a design for a flying robot to create a flying monkey robot[32]. The new design is then added to the database. The bodies of the robots are fabricated as sheets and manually folded. Electromechanical components are then added, and the robot's task is programmed and controlled by the use of traditional perception, planning and control algorithms.

Fabrication

Folded microrobots fabricated by lamination-based processes using polysilicon with polyimide hinges[33–35] are early examples of origami robots. Since the development of these processes, a variety of strategies, such as 3D and 4D printing and laminate manufacturing, have been employed for the fabrication of origami robots.

3D and 4D printing. Rapid fabrication techniques have dramatically improved the design and fabrication of complex robotic systems[36], including origami robots. For example, multi-material 3D printing technology[37] has enabled the direct fabrication of sensors[38–40], actuators[41–43] and integrated robotic systems[31,44–46]. In particular, multi-material 3D printing has been applied to generate smart, flat composites that subsequently fold into 3D shapes[47–50], a process referred to as 4D printing[51,52]. The fourth dimension corresponds to the shape change over time following the printing process. 4D printing enables the rapid fabrication of complex, high-aspect, lightweight composites that would be difficult or costly to directly 3D print (owing to practical challenges, such as build volume or the removal of support material). 4D printing approaches have been investigated for the generation of shape-changing structures for tissue engineering, biomedical devices and soft robotics[53]. However, unlike smart materials, which can usually respond to only one stimulus, robots typically require the coordination of multiple degrees of freedom. In addition to the number of actuated degrees of freedom, origami robots require a certain level of control (that is, repeatability, precision and speed). Such a level of control is currently beyond the capabilities of 4D printing approaches. Nonetheless, smart materials constitute promising actuators for origami robots. Origami folding has also been proposed as a faster alternative to 3D printing for additive manufacturing of soft robots[54].

Laminate manufacturing. An alternative approach to the rapid fabrication of origami robots is the additive and subtractive process of laminate manufacturing, also called smart composite microstructure manufacturing[55]. This approach makes use of the wide variety of currently available rapid, inexpensive, programmable planar fabrication tools, for example, laser machining, printing, lithography and pick-and-place component assembly. This method has been applied for the design of laminate structures that can be folded into hexapod robots[56–58] and insect-scale robots[59,60]. Inspired by pop-up books, single degree of freedom scaffolds have been fabricated for the assembly of these complex robots[61,62].

Actuation

Origami robots use folding to achieve a combination of self-assembly, shape change, locomotion and manipulation. When self-assembly and shape change are not objectives, it is possible to design folded mechanisms with relatively few degrees of freedom, each driven by a single actuator. At the centimetre scale and above, this type of origami robot design shares more similarities with traditional robotic systems. Because fewer actuators are required, this case drives designers towards more complex, commercially available, discrete actuators such as electromagnetic motors[58].

Direct actuation of folded structures with electromagnetic motors has led to crawling robots[63], resilient legged robots[58,64,65], manipulators[66], morphing wheels[5] (FIG. 2e), print and fold robots[68–69] (FIG. 2d) and the locomotion of self-folded structures[70–73]. Patterned pneumatic channels have been used to route pneumatic pressure generated by a discrete commercial pump unit to a number of folds to achieve distributed actuation for origami robots[74]. Similarly, pneumatic pouches, which contract as they inflate, can be used as tendons for the actuation and assembly of origami structures[75,76], or the entire origami structure can be sealed and inflated[77]. However, scaling the pneumatic approach to designs with many actuated degrees of freedom is a challenge. Each actuated degree of freedom beyond the first requires an additional pump or valve component that must be accommodated within the origami robot. Pneumatic actuators have also been integrated with internal origami structures to create soft, compliant and strong artificial muscles that have been shown to lift up to 1000 times their own weight[78].

To realize self-assembly and shape change through folding, distributed actuation is required. The type of actuation depends on the specific application. Even for designs with a low number of theoretical degrees of freedom (for example, the Miura-ori fold pattern[79] (FIG. 2b)), actuators are often required at all — or at a large subset — of the fold edges because friction and deformation necessitate redundancy. Smart material actuators generally have a high energy density and thus can be readily distributed throughout an origami sheet. Smart materials possess one or more properties that change in response to external stimuli (for example, temperature or electric potential)[80], which can be exploited for actuation.

While it may be possible to make a shape-changing device purely composed of a single smart material, in order to make an autonomous robot, it is also necessary to integrate sensing and computation. Thus, for origami robots, smart material actuators are integrated into a planar composite, which contains layers that provide structural support, sensing capabilities, computation and sources of energy[81]. Various smart composite actuation approaches have been explored for the creation of origami robots.

Piezoelectric materials. Piezoelectric materials (that is, materials that change shape in response to an applied electrical charge), such as ceramic perovskite, can be used for the actuation of folded microrobots. Despite having a small stroke, piezoelectric actuators work through folded transmissions to enable insect-scale flying[59,60,82] and legged[83,84] robots. Even though these systems typically have relatively few actuated degrees of freedom, electromagnetic actuators are inefficient at the millimetre scale, leading designers to use piezoelectric actuators as an alternative.

Shape memory alloys. Shape memory alloys (SMAs) are smart materials that can change shape in response to temperature variation[85]. The memory shape is predefined through training at high temperature. After cooling and subsequent heating to a lower transition temperature, stress is induced in the SMA, causing it to return to the trained shape (if unconstrained). Integrated into a smart composite, this effect can be used to actuate folding. However, the low capacity for linear contraction of SMAs (approximately 8%) must be amplified for large deformations. Planar SMA actuators have been used to achieve universal origami sheets[86] and robots[87]. Coiled SMA wires can be threaded through origami sheets to enable shape change[5,88] and to actuate crawling[89,90] and folded-legged robots[56]. However, SMAs are challenging to pattern and integrate owing to the material (metal) and the high training temperature (300 °C).

Shape memory polymers. Shape memory polymers (SMPs), or polymers that undergo shape change in response to a stimuli (often heating), are promising for origami robots as they generally have tuneable properties (for example, actuation strain and activation temperature), are readily patternable and machinable, and are inexpensive to produce. However, they exhibit lower actuation forces than SMAs and are often not bidirectional (that is, external force input is required to reset their shape after actuation). SMPs such as polyolefin[91], polystyrene[70,92] and polyvinyl chloride[93,94] films can be unidirectionally folded at the centimetre to millimetre scale, for example, for one-time assembly. Recently, actuation of folds has been achieved using a bidirectional liquid crystal elastomer[95].

Various other smart materials have been proposed for the actuation of origami robots, for example, dielectric elastomer actuators[96,97], hydrogels[98–100] (in particular for medical applications), polypyrrole films[101,102], magnetoactive elastomer[103] and photothermally[104] or photochemically activated[105] polymers[80,85,106,107].

Sensing

Many origami robots are actuated with open-loop, ON/OFF control without sensor feedback. These systems rely on mechanical stops[92], locking magnets[86] or origami structure interactions to guide the assembly process. However, to create precise fold angles, feedback control through embedded sensors is required. Different sensing modalities have been explored for the sensing of fold angles. For example, layers of microfluidic channels filled with metals that are liquid at room temperature can be used as strain sensors to measure bending[108]. Carbon ink curvature sensors, which are commonly used in commercial electronics, are also very sensitive to bending strain and show high repeatability[87]. Light-emitting diodes (LEDs) and phototransistors, arranged in pairs, are low-cost, low-profile displacement sensors that do not have to be physically located at the folding joints[71]. However, these sensors must be optically protected to avoid noise from ambient light.

Aside from sensing the displacement at the joints of origami robots, sensors can also be integrated into origami composites to enable operation of the robot[109]. For example, compact, flexible piezoresistive sensors[110] can sense loads in folded robot components. Furthermore, hairs that make electrical contact when deflected and force-sensing taxels can be used as tactile sensor arrays for mobile folded robots[109]. Finally, sensors can also be fabricated from folded structures, for example, electromagnetic velocity sensors, mechanical and capacitive switches[111] and capacitive strain sensors[93]. Combinations of these sensor types enable the precise control of shape change, locomotion and manipulation.

Control

Similar to traditional robotic systems, the control of origami robots (assuming rigid faces and discrete joints and folds) includes low-level joint (fold) angle control and coordination of the various joint actuators to regulate the configuration of the robot. Moreover, task-level planning is required to control the behaviour of the robot. Traditionally, robotic systems have a relatively small number of actuated degrees of freedom; for example, a spatial manipulator arm typically has six or fewer and a self-driving car has two actuated degrees of freedom. By contrast, an origami robot can have more degrees of freedom owing to the unconstrained folds of the robot, which leads to challenges in the high-level control of configuration and trajectory planning.

Joint control. Low-level fold angle control can be realized in an open-loop fashion, without sensor feedback. However, feedback control is necessary to enable the precise regulation of fold angles. Most origami robots are made of smart material actuators and thus low-level joint control must often accommodate hysteresis and nonlinearities inherent to many of these materials[80,112,113]. Room temperature liquid metals in microfluidic channels[108], carbon ink curvature sensors[87] and LED-photoresistor pairs[71] achieve feedback control of fold angles within 15.4°, 1.4° and 1.0°, respectively.

External folding. Early work on robotic origami folding considered static sheets of material that could be folded externally (for example, by using robotic manipulators). Such restrictive origami models include robots that can make a sequence of simple folds (that is, folds along a single line)[114] and robots for the automatic folding of cartons and packaging[115]. These robots manipulate the sheet externally, thus relying on external actuation.

Sequential assembly can be directed in a wireless fashion[116]. The folding of origami structures from identical independent units has also been simulated[117], thereby providing a protocol for the self-assembly of the units into a global shape. Different software tools are available for the design of origami robots, which are then fabricated as a sheet and externally folded (typically by hand[30,31]).

Self-folding. Origami sheets with embedded actuation are able to self-fold. Self-folding is the autonomous process that realizes a 3D structure from a 2D sheet without external intervention. Several algorithms for designing self-folded polyhedra have been introduced[118–120]. In self-folding algorithms, the sequence of foldings required during self-folding is computed by a motion planner and controlled using the actuation system embedded in the origami robot. Technical challenges include how to design and embed the actuation system of a 2D origami sheet that supports self-folding of desired 3D shapes, how to program the origami sheet to achieve a specific desired shape and how to control the execution of self-folding. A survey and analysis of prior work on active self-folding structures and methods for the design of self-folding structures is available[107]. A survey of self-assembly for folded microstructures is also available[121,122].

An important consideration that impacts the low-level control of origami robots is whether the flat robotic origami sheet is required to be square (as with traditional origami). There is a trade-off between the complexity of folds and the complexity of the achievable shapes from a square sheet[86]. Origami robots created from a square sheet often involve double folds or multiple folds, which in turn impact the thickness and rigidity of the final structures. Alternatively, the shape of the initial origami sheet could be optimized for the desired 3D shape, which in turn simplifies the required folding.

Another consideration is whether multiple 3D objects need to be created from the same input sheet, in which case the actuation system must be reversible and optimized for the union of operations required. Several algorithms have been introduced to encompass design and control for a self-folding sheet to achieve two shapes[86]. The low-level control for achieving each shape is global, in that one actuation operation triggers all the necessary folds. The actuator is threaded to trigger the correct sequence of folds. This work demonstrated the folding of a boat-shaped object followed by unfolding and the folding of a plane-shaped object from the same origami sheet with a box-pleat structure. This work was generalized as an algorithm that can reshape an origami robot sheet to achieve any k shapes[119]. If, on the other hand, only a single target shape is required, the design and actuation problems are simpler. Irreversible actuation systems can be used (see the Actuation section above for details), and design algorithms can be used to minimize the amount of material and number of folds required, such as in Robogami[31]. While the Robogami systems are manually folded and have hollow interiors, other origami robots use heat-induced self-folding to realize additive structures with built-in joints[54]. The control of heat-activated self-folding is a universal signal that acts on all the joints in the robot. The joint control of different angles is encoded in the origami structure by the size of the cuts in the structural layer of the material[120]. The fold angles are defined by the gap of the top and bottom layers of the material.

Task-level control. Once formed, an origami robot uses the built-in folded structures to execute tasks. Origami robots are able to navigate through their surroundings and manipulate objects. To perform certain tasks, actuation can be controlled locally (by using the built-in joint actuators), in parallel (by using actuators that are connected across multiple joints) or globally (by using external forces). Since origami folding can be used to create all the lower pair joints[123] (FIG. 2c), it is possible to obtain origami alternatives for all types of kinematic structures. The origami kinematic structures can be controlled to achieve their tasks using classical control methods that operate on their joint structures.

A large fraction of the current origami robots have biomimetic inspiration. Origami robot locomotion inspired by biological systems includes origami worms[63,89,90,124–126]; origami legged robots, such as insects[30,58,64,65,68]; origami fish[127] and kirigami robots[128]. These robots rely on their origami folded joints and structural design to locomote. Origami techniques can also be used to create origami wheels[5,68,68]. Origami robot worms[89] use NiTi coil actuators placed on the body of an origami folded worm-like structure to move parts of the structure on demand, and the robot undergoes worm-like peristaltic locomotion. Origami robot earthworms[124] incorporate an origami ball in the body of the robot, which enables locomotion that mimics the locomotion of an earthworm. A gait generator is the robot's 'centralized controller'. Origami balls provide the robot with structural multistability in the axial direction and structural compliance in the radial direction. Other origami robot insects[30,58] have four or six legs and built-in locomotion gaits by design.

The locomotion of these robots is driven by motors added to their bodies. The origami fish[127] is formed by additive folding from a single sheet whose design was optimized to realize the 3D geometry of a fish by zigzag folding. This fabrication approach creates a built-in joint that allows the body of the fish to undulate for swimming. The fish has a small magnet embedded in its body. The direction of swimming can be controlled by an external magnetic field.

The robot OrigamiBot-I is composed of an origami structure actuated by threads that can be wound and unwound using electromagnetic motors, enabling manipulation and locomotion[66]. This design enables twisting and bending motions through applying pulling, pushing or torsional forces to the origami structure. Thread-based actuation also enables various shapes and motions by the use of different numbers of threads and routings through the origami structure.

Devices and applications

Origami robots can be engineered using planar fabrication tools and easy manufacturing processes owing to the fact that folding processes generate the desired 3D structures and mechanisms (FIG. 4). Moreover, origami robots can be transported in a space-efficient flat shape and deployed into 3D shapes as needed. These features make origami-inspired robots interesting components for various devices and applications, ranging from medicine (FIG. 4a,b) to education (FIG. 4d) to space (FIG. 4e–h). Origami devices can be scalable because surface forces (for example, friction, stiction and electrostatic attraction) become relatively more important than body forces (for example, gravity and magnetism) at small scales. Their mechanical components, such as hinges and motors, become less practical at small scales, but the components of origami robots, such as flexure hinges and smart material actuators, remain effective. We can also expect high specific strength. Because origami robots are composed purely of folded surfaces, they tend to be very low mass and can be designed to have relatively high strength. Additionally, complex origami or kirigami mechanisms can be designed to transmit actuation from one source to a variety of locations without the many parts and joints that would be required to do this with a traditional mechanical transmission.

Toys and education. The manufacturability, deployability and high specific strength of origami robots make them ideal for applications in the toy industry (FIG. 4d) and for educational kits. Origami robots can be rapidly and inexpensively manufactured from sheets of material, for example, by roll-to-roll processes, and the low-weight robots can be compactly shipped and assembled by the customer. Folding origami is also a common childhood activity, which makes origami robots engaging and unintimidating. Chuck Hoberman's Sphere and BrainTwist are examples of mass-produced origami toys for solving puzzles and construction, and the Kirigami Robots, which are produced by the company Dash Robotics Inc. and driven by electromagnetic motors, are controllable with a smartphone app (FIG. 4d).

Space robotics. High deployability and specific strength also make origami robots ideal robotic systems for space exploration. Origami fold patterns have been proposed for the packing and deployment of large membranes in space[79]. Furthermore, the self-assembly of mobile robots could be used for extraterrestrial exploration[70] (FIG. 4e). The US National Aeronautics and Space Administration (NASA) is currently developing a centimetre-scale origami robot to be deployed on Mars[129] (FIG. 4f). This rover, named PUFFER (Pop-Up Flat Folding Explorer Robot), has a folded body with a single actuated degree of freedom, enabling it to deploy itself on the surface of Mars and to adjust its body shape in order to squeeze into tight spaces.

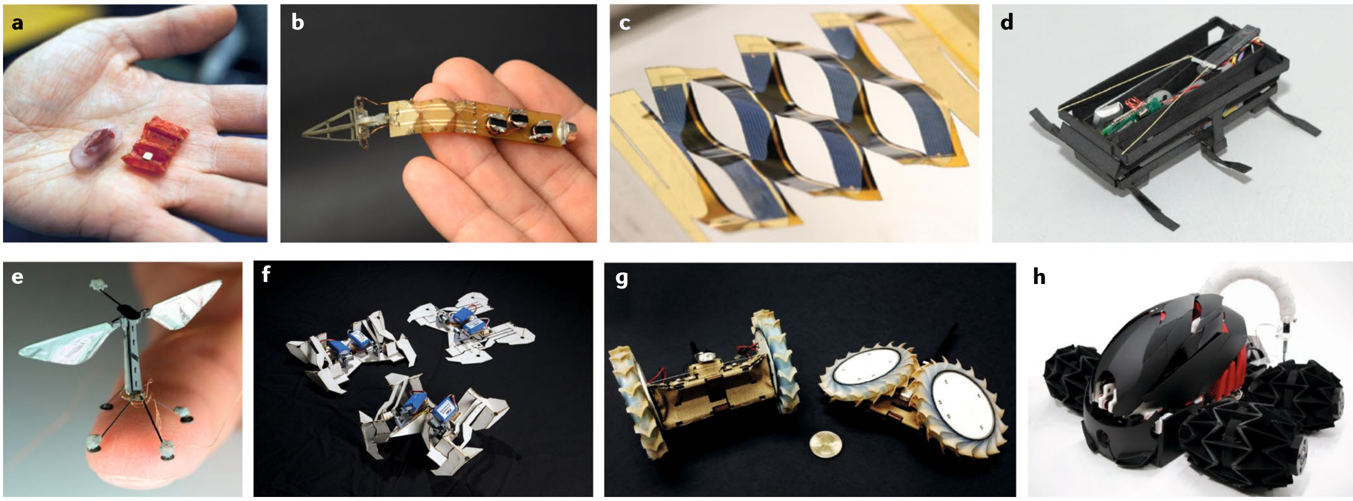

Fig. 4 | **Applications of origami-inspired robots.** Self-deploying ingestible robot[130] (part **a**), wireless-powered gripper for medical applications[135] (part **b**), actuated solar tracking device with flexible kirigami solar panels[137] (part **c**), legged robot toy[58] (part **d**), insect-scale micro unmanned aerial vehicle for surveillance or crop pollination[60] (part **e**), self-assembling robot for search and rescue[70] (part **f**), self-deploying robots for space exploration[129] (part **g**) and origami wheels for performance on unstructured terrain[142] (part **h**). Panel **a** image courtesy of Melanie Gonick, Massachusetts Institute of Technology, US. Panel **b** is reproduced with permission from the Wyss Institute of Harvard University, US. Panel **c** is reproduced from REF.[137], CC-BY-4.0. Panel **d** image courtesy of Betakit. Panel **e** image courtesy of Robert Wood and Kevin Ma, Harvard University Boston, US. Panel **f** is reproduced with permission from the Wyss Institute at Harvard University. Panel **g** is reproduced with permission from NASA/JPL-Caltech. Panel **h** is reproduced from REF.[142], CC-BY-4.0.

Medical devices. Origami robots have been proposed for medical device applications, which often require complex, small-scale devices that can be deployed within the human body. For example, self-folding has been proposed to create origami pills that can deploy as robots inside the stomach[130] (FIG. 4a). These ingestible robots can be controlled to remove foreign objects from the body, patch wounds or deliver medicine to specific locations, which could enable new approaches to incision-free surgery. Folded grippers, which are less than 1000 μm in the folded state, have been developed for drug delivery[131,132]. Although not actively controlled, other work has proposed SMA-driven self-assembly for the deployment of stent grafts to open blocked lumina (for example, arteries)[133]. Pneumatically actuated pop-up folded structures have been proposed to improve the distal dexterity of endoscopes and enable tissue retraction[134]. Other work has demonstrated control of folding with wireless power transmission, enabling remote operation inside the human body without the need for energy storage or control electronics[135] (FIG. 4b).

Unmanned micro air vehicles. The Flying Monkey, which is an origami robot capable of locomotion and flight[32], can be used as an insect-scale micro unmanned aerial vehicle (UAV), owing to scalability and high specific strength, to, for example, pollinate crops[59,60,82] (FIG. 4e). Actuation through folded smart materials offers an efficient alternative to electromagnetic motors and propellers at the millimetre scale. While controlled flight has been achieved, sufficiently energy-dense power sources to enable useful-duration flights remain a challenge. The result is that most insect-scale flying folded robot prototypes to date have been tethered.

Morphable wheels. Actuated origami structures can be designed as soft wheels with variable diameters for applications in unpredictable terrain[5] (FIG. 4h). For example, a waterbomb origami pattern can be folded into an airless wheel with an adjustable diameter. This structure is a key component of the SNUMAX robot, which won the 2016 RoboSoft Grand Challenge[5] — a competition held by RoboSoft, a Coordination Action for Soft Robotics funded by the European Commission. Similarly, origami has been used for the design of a pop-up rover[136].

Actuated solar panels. The ability of a kirigami design to distribute actuation from one source to an array of outputs can be explored for solar tracking in flexible solar panels[137] (FIG. 4c). By applying a specific kirigami cut from a single sheet of a flexible solar panel, the angle of the solar panel can be controlled within ±1°.

Origami exoskeletons. Changing the inherent physical capabilities of robots by metamorphosis has been a long-standing goal of engineers. This task is challenging because within the robot body, each component has a defined and fixed functionality. Self-folding origami structures have been introduced as exoskeletons, enabling new capabilities for the robots, for example, to move faster, to roll, to fly or to glide[73]. This work shows that it is possible to make simpler robots for a multitude of tasks by creating a basic origami robot body and fine-tuned origami exoskeletons that the body can pick up and drop off. By selecting the appropriate materials, a robot can attach exoskeletons using heating on a heating pad and remove them using water and vibratory movement. A robot extended with origami exoskeletons has different locomotion modalities: faster locomotion, locomotion to scoop objects, rolling locomotion, floating and gliding.

Future directions

Origami robots redefine how we make and use robots. Origami machines with built-in compliance and rigidity can be used for physical tasks that require softness and rigidity from the robot body. Inspired by origami, ongoing work in robotics seeks to develop systems that fold controllably from flat sheets into 3D shapes to address challenges in fields ranging from architecture to manufacturing and medicine to transportation and space exploration. These applications are driven by attributes such as manufacturability, deployability, scalability, compliance, specific strength and parallel task-level control. Successes in origami robotics so far include the design, fabrication and control of millimetre-scale to centimetre-scale to metre-scale prototypes, with initial products (for example, toys) already reaching the market.

However, technical challenges remain. For the body, we need tools to design and fabricate origami robot bodies that match their structure to a given task, are self-contained and can be made from a wide range of materials. To meet the potential suggested by the theory of computational origami, we need computational materials with embedded electronic components that are production ready; able to communicate, compute, sense and act; and have programmable material properties. Moving from theory to practice also requires revisiting the assumptions of the theoretical algorithms, especially considering how the physical aspects of the planar substrate impact what is achievable by folding. The theoretical universality of origami design and the large range of envisioned applications for origami robots have not been matched by design and fabrication. While it is possible to prove that any shape can be folded from a flat sheet and to develop practical algorithms to generate unfoldings, there are still many challenges in the design, manufacture and control of origami robots. For example, compound folds are possible in theoretical origami but very challenging for physical origami robots, limiting the reconfigurability of these systems.

For the brain, that is, for the computational algorithms that constitute the brain, we need realistic physical models that can better inform the control algorithms for folding and task execution. The design of appropriate fold patterns for origami robots remains a challenge. Computational origami provides support for automated design using box pleating, but this approach is not optimized for fabrication. As with many design problems, this one is open-ended and difficult to optimize. While origami robot designers often look to origami designs for inspiration, there is still a lot of human creativity and expert intuition required to generate effective designs. Furthermore, commercial CAD tools are not well-suited to the design of origami robots. Progress will be enabled by algorithms that map functional specifications to the design of devices conforming to mechanical constraints (that is, folding along origami creases), new approaches to automate the fabrication of structures as flat sheets with embedded joints, actuation, sensing and computational capacity, as well as additional algorithms for task-level planning and control.

For real-world applications, we need more mechanically robust systems as well as intuitive user interfaces enabled by algorithms for the specification, design, fabrication and control of origami robots. For systems that seek to precisely control the angle of every fold, the complexity of the robot increases dramatically with the number of folds, and power, sensing and computation are required to control and coordinate the actuation of each fold. Actuation also remains a considerable challenge for these systems. Many smart materials have been proposed, each of which has its own advantages and disadvantages. No clear favourite has emerged, which complicates the comparison of alternatives. For systems that simultaneously actuate many folds, traditional electromagnetic motors are more practical. However, the resulting systems begin to resemble soft robots[4], which come with their own set of challenges.

Building on theoretical and computational data, a deeper understanding of origami folding will give rise to a new generation of origami robots tailored to address specific problems in a variety of fields. The manufacturing of shapes, actuators and sensors at small scales is constantly being improved and will enable controllable robotic origami metamaterials[138,139] for the design of deployable and responsive structures, medical devices and haptic interfaces.

A better understanding of the interactions between materials and machine, body and brain, and specification and application will allow the design of customizable robots, ranging from rigid and semi-rigid to soft. The computational approaches to design, fabrication and control are changing the way robots are built, transported and used. Improvements in computational algorithms will make it possible to reduce design and fabrication time from months to days. Robotic systems will be fabricated at a wide range of scales and from various materials, such as titanium, plastics, paper and indigestible animal by-products (for example, sausage casing). This range of possibilities has applications in manufacturing, health care, education and beyond. Because origami robots are easy to design and manufacture, they have the potential to enable customized production. Because origami robots can be created on a small scale from indigestible materials, they have the potential to support incision-free surgical procedures. The ease of design and fabrication out of paper and other widely available materials makes origami robots a perfect education tool for the teaching of design, computation and how machines interact with the physical world.

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